BOARD OF WATER SUPPLY
KA ʻOIHANA WAI
CITY AND COUNTY OF HONOLULU

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Phone: (808) 748-5000 • www.boardofwatersupply.com

June 17, 2024

Ms. Dawn N. S. Chang, Esq.
State of Hawaii Department of Land and Natural Resources
Commission on Water Resource Management
1151 Punchbowl Street
Honolulu, Hawaiʻi 96813

Dear Ms. Chang:

Subject: Order to Honolulu Board of Water Supply to Bulkhead Haʻikū Tunnel (Well No. 2450-001) at the 10-Foot Thick Dike 1,200 Feet from the Portal Entrance and Reduce Their Withdrawal to 0.3 Million Gallons per Day

As part of the Honolulu Board of Water Supply's (BWS's) response to the Commission on Water Resource Management's (CWRM's) Order issued on June 15, 2021, we are hereby submitting our Haʻikū Tunnel Bulkhead Preliminary Engineering Study Technical Report. Previously, we submitted a draft copy of this report to CWRM staff for comment. CWRM's comments and our responses are submitted with the Technical Report as a separate document.

We appreciate the opportunity to respond to CWRM's Order and are available for further questions or comments.

Very truly yours,

ERNEST Y. W. LAU, P.E.
Manager and Chief Engineer

Attachments:
Notice of Commission Action, Haʻikū Tunnel, June 15, 2021
CWRM comments to draft Technical Report / BWS Responses
Haʻikū Tunnel Bulkhead Preliminary Engineering Study Technical Report

STATE OF HAWAII
DEPARTMENT OF LAND AND NATURAL RESOURCES
COMMISSION ON WATER RESOURCE MANAGEMENT
P.O. BOX 621
HONOLULU, HAWAII 96809

June 18, 2021

Ref: PAIFS.5666.3

Ernest Y.W. Lau, P.E.
Manager and Chief Engineer
Honolulu Board of Water Supply
630 S. Beretania Street
Honolulu, HI 96843-0001

Aloha Mr. Lau:

NOTICE OF COMMISSION ACTION
Order to Honolulu Board of Water Supply to Bulkhead
Haʻikū Tunnel (Well No. 2450-001) at the 10-foot Thick Dike 1,200 feet
From the Portal Entrance and Reduce Their Withdrawal to 0.3 million gallons per day
Heʻeia Hydrologic Unit, Koʻolaupoko, Oʻahu

This letter serves as your notice of action taken by the Commission on Water Resource Management (Commission) on the subject matter. On June 15, 2021, by a 7-0 vote (1 vote for approval with reservations), the Commission approved the following Order:

Heʻeia Stream supported one of the most agriculturally productive areas on Oʻahu. The Haʻikū Tunnel, dug at an elevation of 550 feet, depleted the groundwater storage of high-elevation dike compartments which supplied baseflow to Heʻeia Stream. In 1971, the USGS recommended that bulkheading at a 10-foot thick dike compartment at approximately 1,200 feet from the tunnel entrance is the preferred method to restore the storage function of the aquifer. Tunnels with high recession constants (*b*), such as the Haʻikū Tunnel, drain faster than tunnels with lower recession constants, and would therefore benefit more from bulkheading. An existing bulkhead installed and valved at 600 feet from the portal provides some small storage. The substantial ecological and cultural values supported by Heʻeia Stream, including habitat for native amphidromous species, restored native riparian environment, a healthy estuarine and near-shore ecosystem, recreational and aesthetic values, as well as the productivity of the Heʻeia fishpond and wetland to support a biocultural food production system, merits restoration of Heʻeia Stream to pre-tunnel baseflow. In order to protect these instream uses staff recommends that Honolulu Board of Water Supply (HBWS) bulkhead the 10-foot thick dike compartment at approximately 1,200 feet from the tunnel entrance and valve separately from the bulkhead at 600 feet from the tunnel entrance. Such action would increase spring flow in Haʻikū while providing a more reliable source of water supply for HBWS. This solution is expected to increase the natural capacity of the high-elevation groundwater system to store and discharge water to streams and springs in the moku of Koʻolaupoko.

As an interim measure, until the Haʻikū tunnel is fully bulkheaded, Commission staff recommends that HBWS reduce their withdrawal from the Haʻikū tunnel to 0.3 million gallons per day (mgd) by August 15, 2021. When the bulkheading process commences, the Haʻikū tunnel will not be a viable source for HBWS, and therefore the entirety of the tunnel flow will be discharged into the stream.

In order to improve transparency among stakeholders, staff recommends that HBWS provides the daily amount of water withdrawn from each well source (Haʻikū Tunnel, Haʻikū well, and Iolekaʻa well) at monthly intervals.

Following the bulkheading of the tunnel, staff will evaluate the resultant effects on stream baseflow and may amend the interim IFS or amend the HBWS water use permit as needed.

IMPLEMENTATION

- Within two years, HBWS will complete their feasibility study and preliminary engineering design for the proposed bulkhead.
- HBWS will communicate with the Commission and continue to coordinate with Kamehameha Schools, Department of Hawaiian Home Lands (DHHL), Papahana Kuaola, Hawaiʻi Community Development Authority (HCDA), National Estuarine Research Reserve (NERR), and Kākoʻo ʻŌiwi water users on a quarterly basis.
- Upon completion of the feasibility study and engineering design, HBWS will have three years to complete the final design and construction of the bulkhead.
- Following the installation of the bulkhead, staff will work with HBWS, Kamehameha Schools, DHHL, Papahana Kuaola, HCDA, NERR, and Kākoʻo ʻŌiwi to evaluate the implications for baseflow in Haʻikū Stream and determine the feasibility of establishing a numeric instream flow standard.
- If HBWS determines that bulkheading is not a feasible solution upon completion of the feasibility study, staff will recommend an amendment to the interim IFS or amend the HBWS water use permit as needed.

MONITORING

- Streamflow monitoring shall be maintained by HBWS coordinating with USGS.
- At monthly intervals, HBWS will provide monitoring of daily flow withdrawn from the Haʻikū Tunnel, Haʻikū well, and Iolekaʻa well.
- Periodic biological surveys shall be conducted, subject to available funding, to monitor the response of stream biota by all interested parties.
- All claimants shall cooperate with staff in conducting appropriate investigations and studies, particularly with regard to granting access to stream channels and private property related to such investigations, subject to the provisions of the State Water Code, Chapter 174C, HRS.

<u>EVALUATION</u>

- One to two years following the completion of the bulkheading, staff shall report to the Commission on an evaluation of baseflow conditions in He̢ʻeia and nearby streams and make recommendations to amend instream flow standards at that time.

Staff will report to the Commission, at its September 2021 meeting, on the progress of:

1. HBWS reduction to 0.3 mgd from Haʻikū Tunnel;
2. HBWS reduction from Haʻikū Tunnel to flow in Heʻeia Stream;
3. Assessment of bulkhead feasibility and preliminary engineering report; and
4. Potential development of alternative water sources, including the State Hospital Well.

If you have any questions, please contact Ayron Strauch at (808) 587-0265, or ayron.m.strauch@hawaii.gov.

Ola i ka wai,

[signature]

M. KALEO MANUEL
Deputy Director

Ha'ikū Tunnel Bulkhead

Preliminary Engineering Study: Preliminary Draft 010 Comments and Responses

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ITEM	PAGE NUMBER	INITATED BY COMPANY	INITATED BY	COMMENT	RESPONSE BY	RESPONSE
1	5	CWRM	CS	CWRM acknowledged the end uses of the Haiku Tunnel as part of the evaluation of the water system in the submittal and the Instream Flow Standard Assessment Report	JJ	Noted
2	7	CWRM	CS	If conclusions drawn from five years of data are limited in applicability, then how can we draw any conclusions based on the six months of pressure data obtained from Oct 2021 to April 2022 in this report?	JJ	The purpose of the statement was to solely point out the limitation of that study. However, we do not indicate in this report that those conclusions are flawed or suspect. In fact, later in the report we concur that there most likely is connectivity.
3	8	CWRM	CS	comments regarding the temporary nature of an impact during a potential future construction activity are not relevant to this report	JJ	We respectfully disagree. A feasibility report should discuss the risks and impacts for each option to appropriately assess those options. Depending on the option selected, reconstruction that requires tunnel entry could be significant in duration. After construction is completed flushing, chlorinating, and testing for compliance would also be required. Additionally, If the source is down for 12 months or more, then recertification of the source would be required prior to its use.
4	8	CWRM	CS	Temporary unintended consequences are always possible during a construction activity. Mitigation measures can be made, but such factors should not be the subject of this report	JJ	We respectfully disagree. A feasibility report should discuss the risks and impacts for each option to appropriately assess those options. (See response to Comment No. 3)
5	9	CWRM	CS	Can't draw conclusions based on six months of pressure readings during a drought period	JJ	We respectfully disagree with this comment. Regardless of the time frame, trends can be evaluated and and hypotheses can be drawn. This report qualifies that the reason that storage is not accumulating is unknown and recommends that additional time is allowed for recharge and monitoring to better assess connectivity.

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ITEM	PAGE NUMBER	INITATED BY COMPANY	INITATED BY	COMMENT	RESPONSE BY	RESPONSE
6	19	CWRM	CS	This seems to indicate that even at 28-30 psi behind bulkhead activated springs at the 600 and 750ft altitude	JJ	The note on the drawing where the comment is located only indicates that some springs were reactivated at 28 to 30 psi of tunnel pressure. This pressure would be indicative of a water column height between 65 ft and 70 ft. Given that the tunnel elevation is at about 550 ft, it would suggest a top of groundwater elevation between 615 ft and 620 ft considering hydrostatic conditions. The note below the comment on the map indicates that springs existed between 600-ft and 750-ft. Neither note indicates at which elevation springs were reactivated at 28 to 30 psi. The data would suggest that the lower elevation springs were those that were activated. Additionally, This data was collected circa 1944, which is prior to most of the tunnel activity and well development in the area.
7	21	CWRM	CS	is it possible that the tunnel was cut into a buried perched aquifer with the AA overlaying an ash layer?	JJ	At this time the only information regarding the subsurface conditions observed from within the tunnel is provided in Bowles' report.
8	21	CWRM	CS	But no pipeline was constructed from bulkhead 2 to bulkhead 3, and bulkhead 3 is open. Adding a separate pipeline and closing bulkhead 3 may be an option to explore.	JJ	Based on the available information it appears that a pipeline was not installed between Bulkhead No 2 and Bulkhead No. 3. The option of installing 2 pipelines, one from the portal to Bulkhead No. 2 and one from the portal to Bulkhead No. 3 was discussed. Refer to Section 4.3.
9	22	CWRM	CS	So really, Bulkhead 3 would be the most important bulkhead to seal.	JJ	It is possible that this solution provides the best cost-benefit ratio. However, as discussed in Section 4.4 of the report, construction that requires draining the tunnel for entry will likely negatively affect nearby groundwater withdrawal operations, stream flows, and introduce other risks such as tunnel contamination.
10	60	CWRM	CS	It is inappropriate to make determinations of the most appropriate plan to move forward with here; what about providing separate piping between second bulkead to portal and third bulkhead to portal? a comparison of the financial costs for different actions would be more helpful	JJ	This paragraph makes no determination of the most appropriate plan. It simply lays out an option and indicates that it appears to be the least invasive of the construction options that require tunnel entry. Invasiveness does not solely indicate appropriateness. Section 4.3 provides the suggested option of installing 1 pipe to Bulkhead No. 2 and the a second pipe to Bulkhead No. 3. Cost analyses have been provided for 3 options in the updated report.

ITEM	PAGE NUMBER	INITATED BY COMPANY	INITATED BY	COMMENT	RESPONSE BY	RESPONSE
11	60	CWRM	CS	what are the costs for these? How will you determine if this is needed?	JJ	Ventilation will be required as mandated by Health and Safety Standards. An estimate for ventilation costs that include the flexible lines or cored holes through the bulkheads would likely be performed to provide a range of potential costs. However, these costs would be relatively minor as compared to the overall project cost.
12	74	CWRM	CS	Again, this is speculative based on 6 months of data during a drought. It would be inconsistent to say 5 years of data are insufficient to draw conclusions and then base any conclusions on 6 months of data.	JJ	The intent of this paragraph is not to draw any conclusions. It is meant to be an hypothesis, thus, halfway through the second paragraph we say "it is possible that the volume....". The words "This can" at the beginning of the third sentence can be changed to "This could" to avoid confusion. But again, this is another example of why additional time for recharge, with pressure and flow monitoring, would be beneficial to assess connectivity.
13	74	CWRM	CS	This is speculative and assumes a predetermined water management strategy. If water withdrawals ceased during the wet season, or altogether, additional storage may be realized.	JJ	It is not speculative as it is not portrayed as a conclusion. It is simply a plausible outcome based on the available information. Similarly to the previous comment response, it is meant to demonstrate why additional time for recharge while monitoring is required to further assess dike connectivity.
14	77	CWRM	CS	From a maximum beneficial use perspective, this would be the preferred option without adding a bulkhead (adding two pipelines to control flow discretely	JJ	Noted. However, as discussed in Section 4.4 of the report, construction that requires draining the tunnel for entry will likely negatively affect nearby groundwater withdrawal operations, stream flows, and introduce other risks such as tunnel contamination.
15	77	CWRM	CS	This is such a minor point (0.02 cfs based on USGS) that it doesn't seem worth mentioning	JJ	Noted
16	77	CWRM	CS	This is completely speculative without substantial data to justify it. Also, the rate of withdrawal can always be modified either voluntarily or by order	JJ	We disagree completely with the comment. There is sufficient evidence that connectivity exists. Even if the Haiku Tunnel was shut down full storage may never be realized due to nearby groundwater withdrawal operations. Additional time for recharge and monitoring would likely be beneficial in assessing the effect of dike connectivity prior to implementing a costly construction project that presents many construction related risks as outlined in Section 4.4 of the report.

Ha'ikū Tunnel Bulkhead Preliminary Engineering Study

Ha'ikū Valley, O'ahu, Hawaii

June 2024

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Date: June 12, 2024
File Number: 121297-000

Honolulu Board of Water Supply
630 S. Beretania St.
Honolulu, HI 96843

Attention: Ms. Nancy Matsumoto, P.G., C.HG.
Hydrologist-Geologist

Subject: Preliminary Engineering Study
Ha’ikū Tunnel Bulkhead
O’ahu, Hawaii

Ms. Matsumoto:

Submitted herewith is our Preliminary Engineering Study for the Ha’ikū Tunnel Bulkhead. This Study was conducted in general accordance with the contract between Brierley Associates and the Honolulu Board of Water Supply, dated July 5, 2022. This report contains the results of Brierley’s findings, engineering interpretation with respect to the available project characteristics, and our preliminary design recommendations for potential solutions.

We appreciate the opportunity to work with you on this project. If we can be of further assistance, or if you have any questions, please contact the undersigned.

Sincerely,
BRIERLEY ASSOCIATES CORPORATION

Charles A. Luxford, PE, SE
Sector Lead

Jeremiah Jezerski, PE
Associate

CHARLES A. LUXFORD ★ LICENSED PROFESSIONAL ENGINEER No.12488S ★ HAWAII U.S.A.

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INTRODUCTION

Preparation of this Preliminary Engineering Study for Honolulu Board of Water Supply (HBWS) is in part to satisfy the implementation schedule outlined in the June 18, 2021, Notice of Commission Action issued by State of Hawaii, Commission on Water Resource Management (CWRM). The Order, as presented in Appendix G of this report, set forth a series of actions including a requirement to reduce withdrawal from the Ha'ikū tunnel to 0.3 million gallons per day (MGD) by August 15, 2021, which HBWS has complied with. Additionally, the letter concerns the installation of an additional bulkhead within the existing Ha'ikū Tunnel at a location approximately 1,200-feet from the portal entrance. The intent of the additional bulkhead, as stated in the June 18, 2021 letter, is to "increase spring flow in Ha'ikū while providing a more reliable source of water supply for HBWS".

Key statements from the CWRM order include:

- "Heʻeia Stream supported one of the most agriculturally productive areas on Oʻahu. The Haʻikū Tunnel, dug at an elevation of 550-feet, depleted the groundwater storage of high-elevation dike compartments which supplied baseflow to Heʻeia Stream."
- "The substantial ecological and cultural values supported by Heʻeia Stream, including habitat for native amphidromous species, restored native riparian environment, a healthy estuarine and near-shore ecosystem, recreational and aesthetic values, as well as the productivity of the Heʻeia fishpond and wetland to support a biocultural food production system, merits restoration of Heʻeia Stream to pre-tunnel baseflow."
- "In order to protect these instream uses staff recommends that Honolulu Board of Water Supply (HBWS) bulkhead the 10-foot thick dike compartment at approximately 1,200-feet from the tunnel entrance and valve separately from the bulkhead at 600-feet from the tunnel entrance. Such action would increase spring flow in Haʻikū while providing a more reliable source of water supply for HBWS."

Additionally, the following implementation actions were set forth in the Order:

- "Within two years, HBWS will complete their feasibility study and preliminary engineering design for the proposed bulkhead."
- "HBWS will communicate with the Commission and continue to coordinate with Kamehameha Schools, Department of Hawaiian Home Lands (DHHL), Papahana Kuaola, Hawaiʻi Community Development Authority (HCDA), National Estuarine Research Reserve (NERR), and Kākoʻo ʻŌiwi water users on a quarterly basis."
- "Upon completion of the feasibility study and engineering design, HBWS will have three years to complete the final design and construction of the bulkhead."
- "Following the installation of the bulkhead, staff will work with HBWS, Kamehameha Schools, DHHL, Papahana Kuaola, HCDA, NERR, and Kākoʻo ʻŌiwi to evaluate the implications for baseflow in Haʻikū Stream and determine the feasibility of establishing a numeric instream flow standard."

- "If HBWS determines that bulkheading is not a feasible solution upon completion of the feasibility study, staff will recommend an amendment to the interim IFS or amend the HBWS water use permit as needed."

It should be noted the Order did not mention that the HBWS Ha'ikū Tunnel provides important freshwater supply for domestic uses in the higher elevations of Ha'ikū Valley to Maunawili. Domestic Use is one of four Public Trust Uses of freshwater, in addition to water in its natural state, traditional and customary uses and water for DHHL, as determined by the Hawaii State Supreme Court in the Waiahole Ditch Contested Case, August 2000. CWRM must therefore balance freshwater supply among all four public trust uses before allocating water to non-public trust uses of agriculture, commercial and industrial uses.

In response to the Order, HBWS contributed $525,000 to an $875,000 cooperative study with the USGS to evaluate He'eia Stream flow, conduct stream seepage runs and install a second permanent stream gage on the He'eia Stream below the confluence with the Ioleka'a Stream. As of this writing, the USGS report is pending publication. HBWS will also be co-funding the ongoing monitoring of the two USGS stream gages along the He'eia Stream.

Concurrently, HBWS funded this Ha'ikū Tunnel Bulkhead Preliminary Engineering Study. Preparation of this this report entailed the review of existing available information as cited. Some of the documents reviewed were compiled from HBWS files and had not been previously published. Remaining documents were public reports, such as those issued by the United States Geological Survey (USGS), were provided to Brierley Associates by HBWS, or obtained from USGS or other web-based libraries and sources.

This report was prepared by Brierley Associates Corporation (Brierley) for HBWS. Brierley specializes in underground design and construction engineering, including tunnels and shafts in rock and soft ground for water and wastewater conveyances.

EXECUTIVE SUMMARY

Preparation of this report entailed the review of existing available information as cited. Some of the documents reviewed were from HBWS files and had not been previously published. Public reports, like those issued by the USGS were provided by the Board of Water Supply, obtained from the USGS, or obtained from other on-line library resources.

One noteworthy unpublished HBWS report "Haiku Tunnel Study" by Stephen P. Bowles, HBWS Hydrologist-Geologist, dated April 1969 is believed to provide the most accurate information for this study. As Bowles physically entered the tunnel and directly observed the conditions inside, and George Hirashima, who authored or co-authored papers about the Ha'ikū Tunnel in 1962,1963, 1969 and 1971 did not, Bowles' statements are given significant consideration.

The Ha'ikū Tunnel is one of many tunnels constructed along the windward side of O'ahu. Construction commenced in 1939 and was completed in late 1940. The tunnel extends approximately 1,200-feet with 3 bulkheads installed along its length and three branch tunnels mined in attempt to reach perceived and/or investigate potential water source(s). Geological mapping and hydrological analysis by several entities discovered that dikes, created by the upward flow of magma through vertical cracks of existing lava flows, function as groundwater control mechanisms, or reservoirs filling as rainwater percolates through the ground. Tunneling through these dikes act as horizontal wells to allow water to flow by gravity into the HBWS water system. Figure 1, provided in Section 1 of the report, helps to illustrate surface water, groundwater, and dike interactions.

Review of the provided field and background maps cited within this report, led to the interpretation that bulkheads were installed within the Ha'ikū Tunnel at STA 0+30 (Bulkhead No. 1), Sta 6+00 (Bulkhead No. 2) and STA 9+00 (Bulkhead No.3). Further, information from the June 1966 HBWS Water Resources Division sketch of the Ha'ikū Tunnel and the Bowles 1969 report provides additional insight, as follows:

- The section of tunnel between Bulkhead No. 1 and Bulkhead No. 2 was concrete lined to utilize as a groundwater conveyance and mitigate loss of water between Bulkheads No. 1 and No. 2. During initial operation and testing it was found that the lined section experienced significant leakage through this liner, therefore, a 12-inch diameter conveyance piping was installed from the portal to Bulkhead No. 2 to mitigate water loss through this section of tunnel.

- Bulkhead No. 3 is open since a 9-foot-long segment of 36-inch diameter pipe reportedly extends through the bulkhead, allowing impounded water to flow through and potentially allow physical access to the back of the tunnel.

- Following the construction of bulkheads, concrete lining, and piping in 1940, the tunnel was shut in and a pressure of 90 to 95 psi was recorded. Although not completely documented, the ability to shut-in the tunnel and then take a pressure reading most likely occurred outside the tunnel portal entrance at elevation 550-feet MSL. The tunnel was then opened and a flush flow of 11.9 MGD was measured. After detecting leakage around Bulkhead No. 1, the piping was replaced through Bulkhead No. 2 and sealed. After a week it was found that at pressures of 20 to 25 psi, He'eia stream would begin to flow in a manner similar to that recorded by the USGS in 1938 (Bowles, 1969). Bowles apparently confirmed this as on May 2, 1969, when after his inspection the valves at Bulkhead No. 2 were closed and the tunnel was allowed to recharge. Bowles states: "Leakage to the Ha'ikū stream was well established at a tunnel pressure of 25 psi or 58-feet of water."

- Bowles found that there was no dike at the end of the tunnel at (STA 12+00), contrary to what was reported (based on interpretation of old construction notes, and not field verified) by Hirashima (1971). Rather, Bowles observed that "the last 20-feet of tunnel is cut in clinker; Apparently, the sudden contrast in permeability and rapid increase in flow gave the impression that a dike compartment had been tapped." **This is a noteworthy observation as assessment and conclusions made by Hirashima and CWRM recommend that a new bulkhead be constructed near the end of the tunnel ~STA 11+78 based on the assumption that a thick dike is present.**

Evaluation of tunnel withdrawal rate, tunnel pressure and stream flow measurements have indicated the following:

- Pressure monitoring data, as provided by HBWS, reveal that during the tunnel shut down between October 2021 through April 2022 the tunnel reached an internal pressure of about 47 psi. This pressure is lower compared to the 90 psi shut-in pressure reported in December 1940. However, the effects of potentially hydraulically connected tunnels and wells that were installed in Ha'ikū Valley and nearby valleys post-1940, as well as the extended period of drought during 2021 and 2022, likely affected the maximum pressure recorded during the October 2021 to April 2022 Ha'ikū Tunnel shutdown. Since April 2022, the withdrawal rate has been steady at 0.35 MGD and monitoring at the portal has indicated a relatively steady groundwater pressure of 43 psi. Given the interconnectivity between the dike compartment that supplies the Haʻikū Tunnel and those that supply streams and groundwater withdrawal operations in the Kahalu'u, and Ioleka'a Valleys the 90 psi internal pressure measured during initial shut-in may never be realized with today's conditions.

- Based on the available information it appears that there has been a reduction in the He'eia Stream flow since the withdrawal of water from the Haʻikū Tunnel began in December 1940. Significantly lower He'eia Stream flows were observed shortly after construction of the Haʻikū Tunnel until about 1963, whereas since 1964 stream flows have been relatively steady with a Q_{90} generally between 1.0 MGD and 2.0 MGD. As part of USGS Water-Supply Paper 1894 (Takasaki et al, 1969), the long-term Q_{90} of the stream was calculated as 1.2 MGD for the base period between 1927 and 1960 based on correlations with the East Branch Manoa Stream, which is similar to the Q_{90} values calculated since 1964. It should be noted that the tunnels installed in neighboring valleys post-1940 (e.g., Luluku Tunnel c.1945, Kahaluu Tunnel c.1946, Waihee Tunnel c.1955), were completed and were likely in operation by this time.

- Estimates by Hirashima (1963) suggest that a recharge rate of 2 MGD exists based on withdrawal rates between 1953 and 1958 and if withdrawal from the Haʻikū Tunnel were to cease it would take approximately 2 years to fully recharge the dike compartments. However, as indicated by Izuka et. al (1993) some of that recharge may be supplied from other drainage basins, such as the Kahalu'u, and Ioleka'a Valleys due to extension of the dike compartment to those valleys or interconnectivity between dike compartments along the Ko'olau Range.

- Estimated recharge rates pertaining solely to the Haʻikū Valley indicate that the dike compartment(s) which supply groundwater to the Haʻikū Tunnel must extend to or are connected to nearby valleys along the Ko'olau Range.

- Since the early 1990's measured water withdrawal rates considering only the Haʻikū and Kahalu'u Tunnels shows that as groundwater withdrawal rates were reduced from the Haʻikū Tunnel the groundwater withdrawal from Kahalu'u Tunnel was increased nearly at the same rate. The likely connection or continuity of the dike compartments that supply the groundwater to both tunnels, could explain why internal tunnel pressure within Haʻikū Tunnel has not increased as groundwater withdrawal from it has decreased.

Publications issued by USGS concerning windward side of O'ahu water resources were key to providing the following:

- Hirashima, 1962, performed a study that concluded that the construction and operation of the Ha'ikū Tunnel reduced the flow in the Kahalu'u Stream which is about 2.5 miles away from Ha'ikū Tunnel. It should be noted that this study is based on a relatively short time period, July 1936 and June 1946, and only provides approximately 5 years of data after Ha'ikū Tunnel construction. The limited duration of data might have been driven by the construction of the tunnel in the in the Kahalu'u Valley in 1946, refer to Table 1 and Figure 5. Later, a tunnel in the Waihee Valley was constructed during 1954 to 1955.

- Hirashima, 1963 expanded the information presented in his 1962 publication and concluded: "It is evident, also, that the flows of the Ha'ikū, Ioleka'a and Kahalu'u Streams as well as the Ha'ikū and Kahalu'u tunnels are derived from and sustained by interconnected ground-water reservoirs."

- If Hirashima is correct that the operation of the Ha'ikū Tunnel reduced flow in the Kahalu'u Stream, then opening the Ha'ikū Tunnel to allow free flow for bulkhead construction could result in significant impacts on the Kahalu'u Stream and functionality of the tunnel in the Kahalu'u Valley.

Historical literature cited were key to developing an understanding of operating characteristics of Ha'ikū Tunnel, groundwater movement, stream flow and precipitation as discussed in Section 1.3 of this report. Based on the available information it appears that there has been a reduction in stream flow since the withdrawal of water from the Haʻikū Tunnel began in December 1940. It is also likely that the dike compartments responsible for providing water to the Haʻikū Tunnel are interconnected to those providing water to the He'eia, Kahalu'u, and Ioleka'a Streams as well as the Haʻikū and Kahalu'u Tunnels.

Summary of Alternatives

As required by the June 18, 2021 Notice of Commission Action issued by CWRM, the feasibility of the installation of an additional bulkhead within the existing Ha'ikū Tunnel at a location approximately 1,200-feet from the portal entrance was evaluated. This Preliminary Engineering Study considered and evaluated the alternatives listed below.

1. Installation of a bulkhead at ~STA 11+78 (CRWM)
2. Installation of a bulkhead at STA 9+80 (Bowles)
3. Installation of pipe from Bulkhead No. 2 through No. 3
4. Construct a new horizontal tunnel
5. No Build/Future Build

These are further discussed in Section 3 of this report.

Fourth Bulkhead Feasibility

It is well established that the majority of the inflow supplying the Haʻikū Tunnel occurs beyond STA 9+80, approximately 97% developed beyond STA 9+50 as reported by Bowles. Therefore, bulkheading in the vicinity of this location has the potential to provide more storage and prevent leakage from dike compartments up-station of STA 9+80 from leaking into shallower compartments. However, reported dike compartment interconnectivity between valleys could prevent storage increase due to withdrawal at other locations. If bulkheading at a dike crossing beyond STA 9+80 is the preferred option, then an inspection of the tunnel should be performed prior to or during construction to confirm whether dikes are in fact located at STA 9+80 and/or STA 11+78.

Numerous challenges to successfully execute the construction of a fourth bulkhead either in the wet or dry include surface access logistics, interior tunnel access and worker safety during construction, regulatory permitting, and possible unintended consequences affecting other streams and tunnels due to the dewatering of the Ha'ikū Tunnel and dike compartments.

Conclusion

This engineering study has examined numerous available historical records and reports in an attempt to understand the existing condition of the tunnel and surrounding hydrogeology for context in evaluating the feasibility of installation of a fourth bulkhead within Haʻikū Tunnel. Water Budget Studies and documented stream flow measurements have demonstrated that the dike compartments supplying groundwater to the Haʻikū Tunnel either extend into nearby valleys or are hydraulically connected to dike compartments in those valleys. It is recommended that additional hydrogeologic studies be performed to assess the interconnectivity associated with the dike compartments. That study, coupled with the forthcoming updated groundwater recharge estimates and associated water budget assessments by USGS may be able to provide additional insight with regards to recharge and interconnectivity associated with the dike compartments providing groundwater to the water supply tunnels and wells within the region.

Installation of a fourth bulkhead within the Haʻikū tunnel requires a considerable investment of resources, incurs substantial risks and ultimately may not be able to achieve any substantial improvement in the storage capacity. With historical records indicating a potential storage pressure of the current tunnel configuration nearly twice what is currently being measured, additional storage capacity would appear possible within the compartments supplying the tunnel but is not being achieved. It is unclear whether additional groundwater storage is not occurring because the groundwater is either leaking out of the dike compartments and/or being extracted from other interconnected existing tunnels and/or wells. Providing additional time for recharge to occur and potentially rebuild storage to a larger fraction of what the existing tunnel configuration originally was capable of maintaining appears to be the best course of action given current understanding of the Haʻikū tunnel conditions.

1 EXISTING FACILITY

This section summarizes the known information with respect to tunnel location, construction history, as-built condition of the tunnel, such as size, bulkhead locations, piping, and other historical information concerning this asset. This section also presents information regarding important geological features such as dike locations, areas of potential clinker, reported water infiltration rates along the tunnel alignment during construction, and reported stream flows prior to construction of the Ha'ikū Tunnel.

Preparation of this report entailed the review of existing available information as cited. Some of the documentation reviewed were from HBWS files and had not been previously published. Public reports, like those issued by the USGS were provided by the Board of Water Supply, obtained from the USGS, or obtained from other on-line library resources.

Ha'ikū Tunnel is one of many tunnels constructed along the windward side of O'ahu. Construction commenced in 1939 and was completed in late 1940. Geological mapping and hydrological analysis by several entities discovered that dikes, created by the upward flow of magma through vertical cracks of existing lava flows, function as groundwater control mechanisms. As rainwater infiltrates down into the ground from the high elevation forest, the dikes essentially impound the groundwater thus changing the direction of flow from downslope, or towards the sea, to a direction parallel with the dikes. Underground water reservoirs are formed between these dikes. Once a tunnel is mined through a dike a bulkhead is typically constructed to control the flow of contained water and to allow the water to accumulate with the expectation that the water level will rise within the rock mass between dikes to form a large vertical reservoir. Pipes are commonly installed through the bulkhead(s) to allow water to flow by gravity to serve users and purveyors of water like HBWS. Figure 1 helps illustrate surface water, groundwater, and dike interactions.

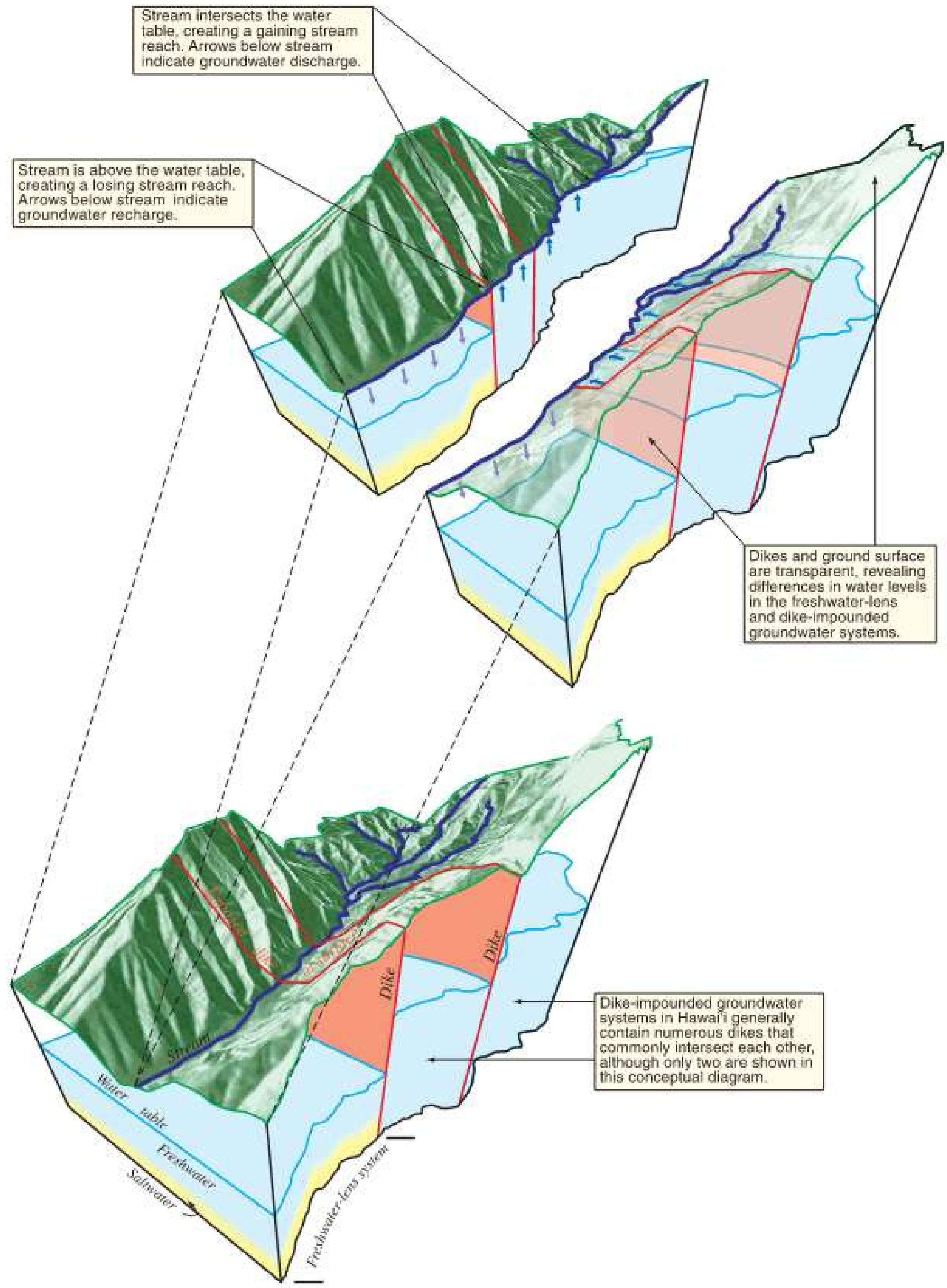

Figure 1: Conceptual diagram illustrating surface water and groundwater interactions (Source: Oki et al, 2010)

1.1 Tunnel Location

The Ha'ikū Tunnel is located on the windward side of the Ko'olau Range in the Ha'ikū Valley west of Kaneohe and He'eia on the island of O'ahu. The location of the tunnel is shown in Figure 2. Figure 3 shows the location of the tunnel with respect to the Ha'ikū Valley.

Figure 2: Tunnel location on O'ahu (Image from Google Earth)

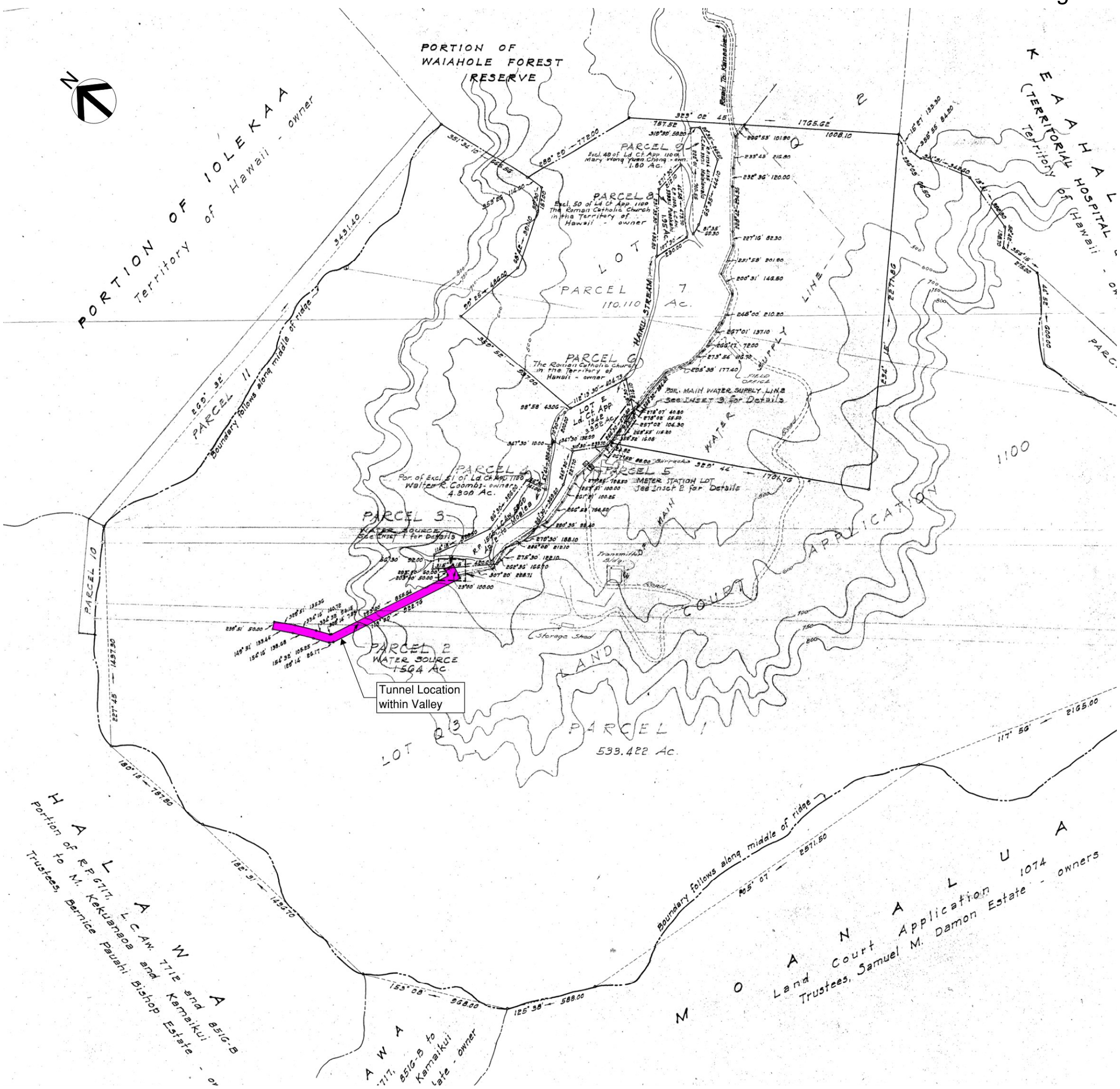

Figure 3: Tunnel location within the Ha'ikū Valley (Source: 1943 Survey Map titled N-00769)

Developing an understanding of Ha'ikū Tunnel construction, performance, and regional geology is predicated on the historical information and sequence of events listed in Table 1. During the course of this Preliminary Engineering Study the HBWS reports cited were used to develop an understanding of the Ha'ikū Tunnel as-built conditions. **It should be noted that the only documented post-construction entry into the Ha'ikū Tunnel was by S.P. Bowles in 1969**. Figure 4 illustrates some of the observations made by Bowles during that inspection.

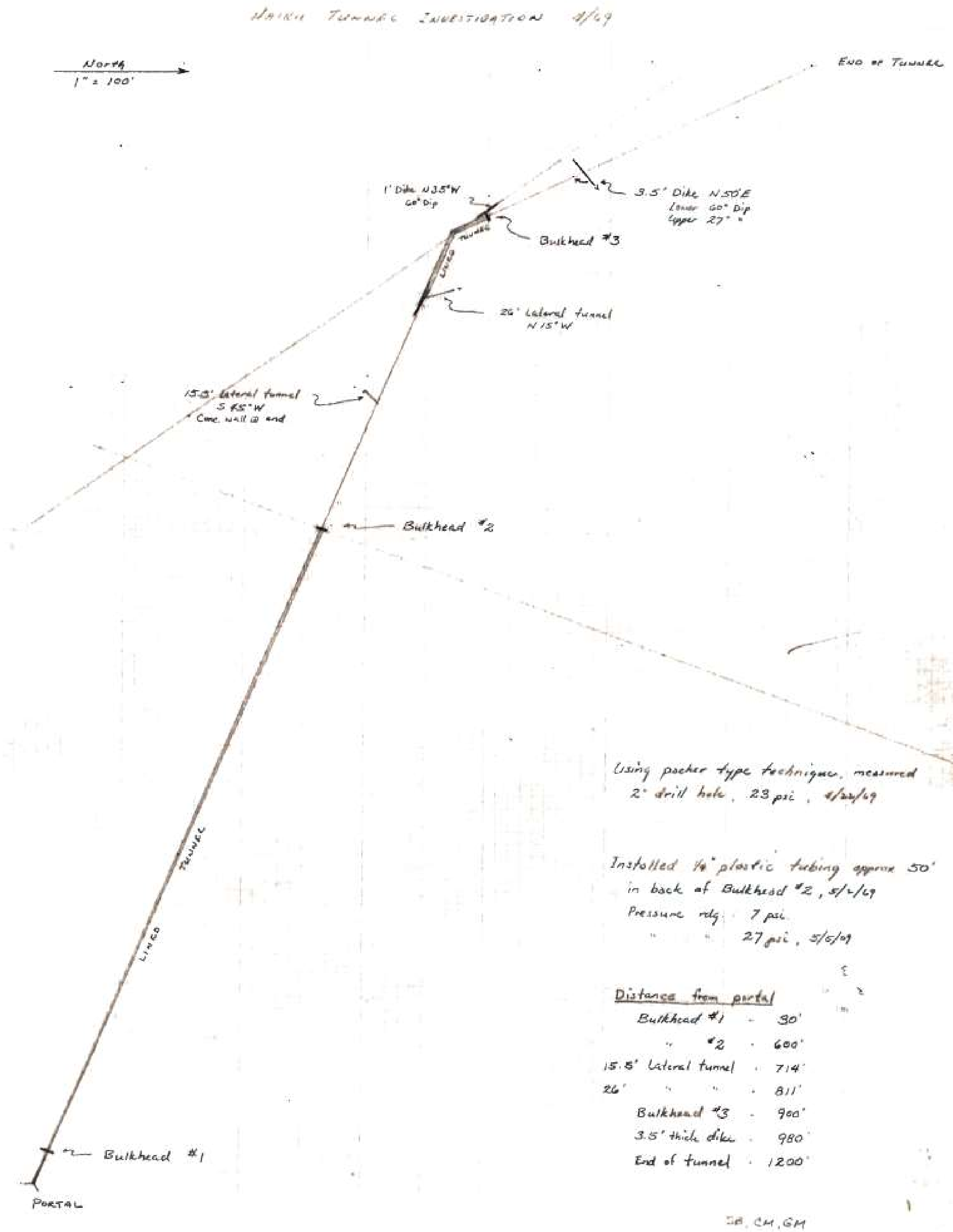

Figure 4: Field sketch map developed by Bowles during entry into the Ha'ikū Tunnel, 1969

Table 1: Timeline of key activities and studies related to the Ha‘ikū Tunnel

Date/Time Period	Activity/Study
1939 to late 1940	Ha’ikū Tunnel Construction by Honolulu Board of Water Supply. As-built map titled “N-00805” produced
1946	Kahalu’u Valley Tunnel Construction by Honolulu Board of Water Supply
1954 to 1955	Waihee Valley Tunnel Construction by Suburban Water System
1962	George T. Hirashima, USGS, Honolulu publishes “Effect of the Haiku Tunnel on the Kahaluu Stream, Oahu, Hawaii”
1963	George T. Hirashima, USGS, Honolulu publishes “Influence of Water-Development Tunnels on Streamflow-Groundwater Relations in Haiku-Kahaluu Area, Oahu, Hawaii”
June 1966	HBWS Haiku Tunnel map prepared by Quon H.D. Holt based on information contained in a memorandum from H.S. Palmer to E.J. Morgan dated August 31, 1958
February 1969	Report titled “Planning for Haiku Tunnel Study” authored by S.P. Bowles, Honolulu Board of Water Supply
April 1969	Report titled “Haiku Tunnel Study” authored by S.P. Bowles, Honolulu Board of Water Supply
1969	Field sketch map prepared by S.P. Bowles, Honolulu Board of Water Supply
1969	K.J. Takasaki, G.T, Hirashima and E.R. Lubke, USGS Honolulu publish “Water Resources of Windward Oahu, Hawaii,” USGS Water Supply Paper 1894
1971	G.T. Hirashima, USGS Honolulu publishes “Tunnel and Dikes of the Koolau Range, Oahu, Hawaii, and Their Effect on Storage Depletion and Movement of Groundwater”, Geological Survey Water Supply Paper 1999-M
1993	Izuka et al. USGS, Honolulu publishes “Geohydrology and Possible Transport Routes of Polychlorinated Biphenyls in Haiku Valley, Oahu, Hawaii.”

Figure 5 illustrates the location of Ha’ikū Tunnel and other water supply tunnels mentioned in the reports cited above.

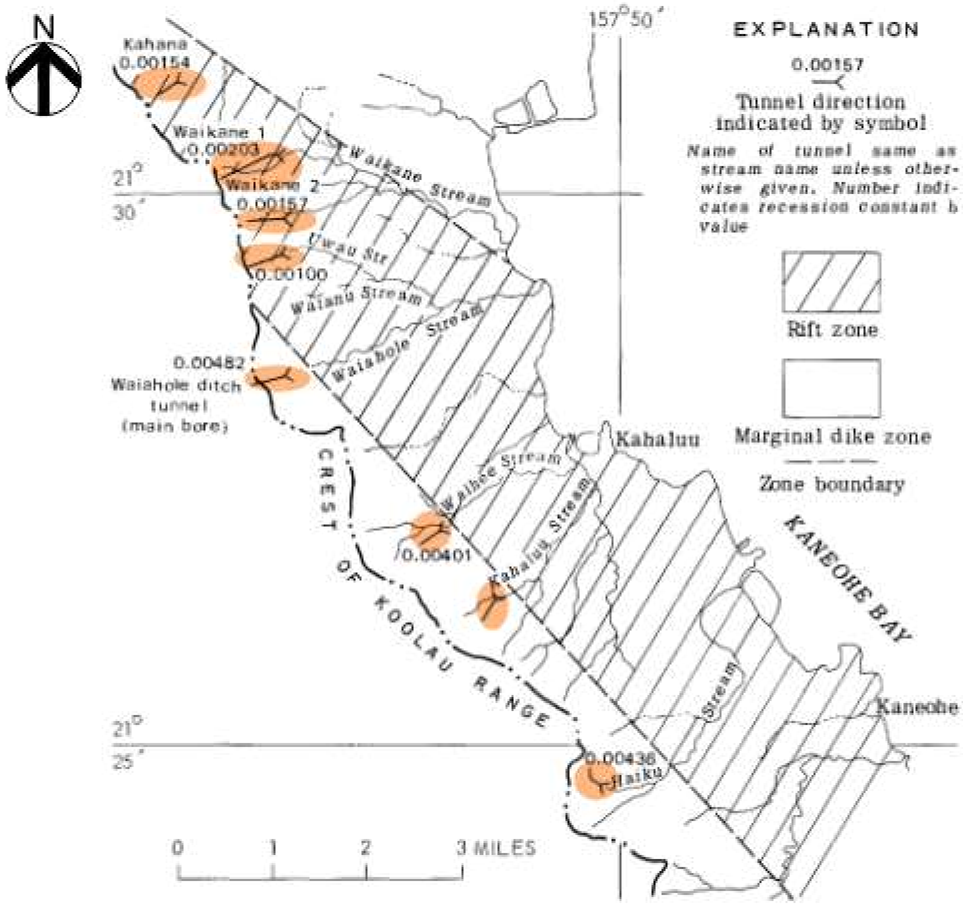

Figure 5: Location of tunnels in relation to rift (dike complex) and marginal dike zones. (Source: Takasaki, Hirashima, and Lubke, 1969)

1.2 Historic Records of Construction & Later Studies

As physical entrance to the tunnel has not occurred since 1969, information contained within available historical documents and references relating to the tunnel were relied upon. The following reference documents are believed to be the most reliable information regarding the current layout and characteristics of the tunnel:

- An undated (circa 1940) tunnel construction record labeled "N-00805" presenting groundwater inflow data during construction; stamped with (inferred to be prepared by) "H.A.R. Austin Consulting Engineer"
- A 1966 Tunnel map prepared by Quon H.D. Holt based on information contained in a memorandum from H.S. Palmer to E.J. Morgan dated August 31, 1958
- Report titled "Planning for Haiku Tunnel Study" by S.P. Bowles, dated February 18, 1969
- Report titled "Haiku Tunnel Study" by S.P. Bowles, dated April 1969
- A 1969 field sketch map prepared by S.P. Bowles

The following section describes our understanding and the most probable as-built conditions based on the reports listed above. Our interpretation of this available information led to the development of figures "Tunnel Plan-Existing Conditions" and "Tunnel Profile-Existing Conditions" which are presented in Appendix A of this report and summarized in Table A-1 and Table A-2, also presented in Appendix A.

1.2.1 Tunnel Geometry

Ha'ikū Tunnel construction commenced in 1939 and completed in late 1940. The tunnel extends approximately 1200-feet with 3 bulkheads installed along its length. According to the historical information three branch tunnels were excavated in attempt to reach perceived and/or investigate potential water source(s). Please refer to Figure 6 for an Interpreted Tunnel Map Based on Review of Historical Documentation, which is also shown in Appendix A.

HBWS provided Brierley with an internal report that documents the 1969 inspection by Stephen P. Bowles of the HBWS Hydrology & Geology Section, Planning, Resources & Research Division (Bowles, 1969). Review of the provided field and background maps led to the determination that Bulkhead No. 1 was installed near the portal at STA. 0+30, Bulkhead No. 2 was installed at STA 6+00, at the first known dike crossing which has a reported thickness of 1.5-feet, and Bulkhead No.3 was installed at STA 9+00. It is not clear whether Bulkhead No. 3 is installed at a dike location, but likely is based on other available information. Specifically, both of the referenced maps that were developed prior to the 1969 inspection show the presence of an approximately 1.5-feet thick dike in the vicinity of Bulkhead No. 3 and the "N-00805" map shows it in very close proximity. The maps developed by Bowles from his observations do not show this dike, which could mean that it was not visible due to Bulkhead No. 3 completely covering it, it was not considered remarkable, or it was simply missed during the inspection.

During mining the tunnel passed through an oblique dike into a relatively dry rock at about STA 7+80. Therefore, the tunnel was redirected, exiting the dry rock through the same oblique dike at STA 9+00. The section of tunnel within the dry compartment, between STA 7+80 and STA 9+00, was subsequently lined to mitigate loss of water from the tunnel into to the dry rock.

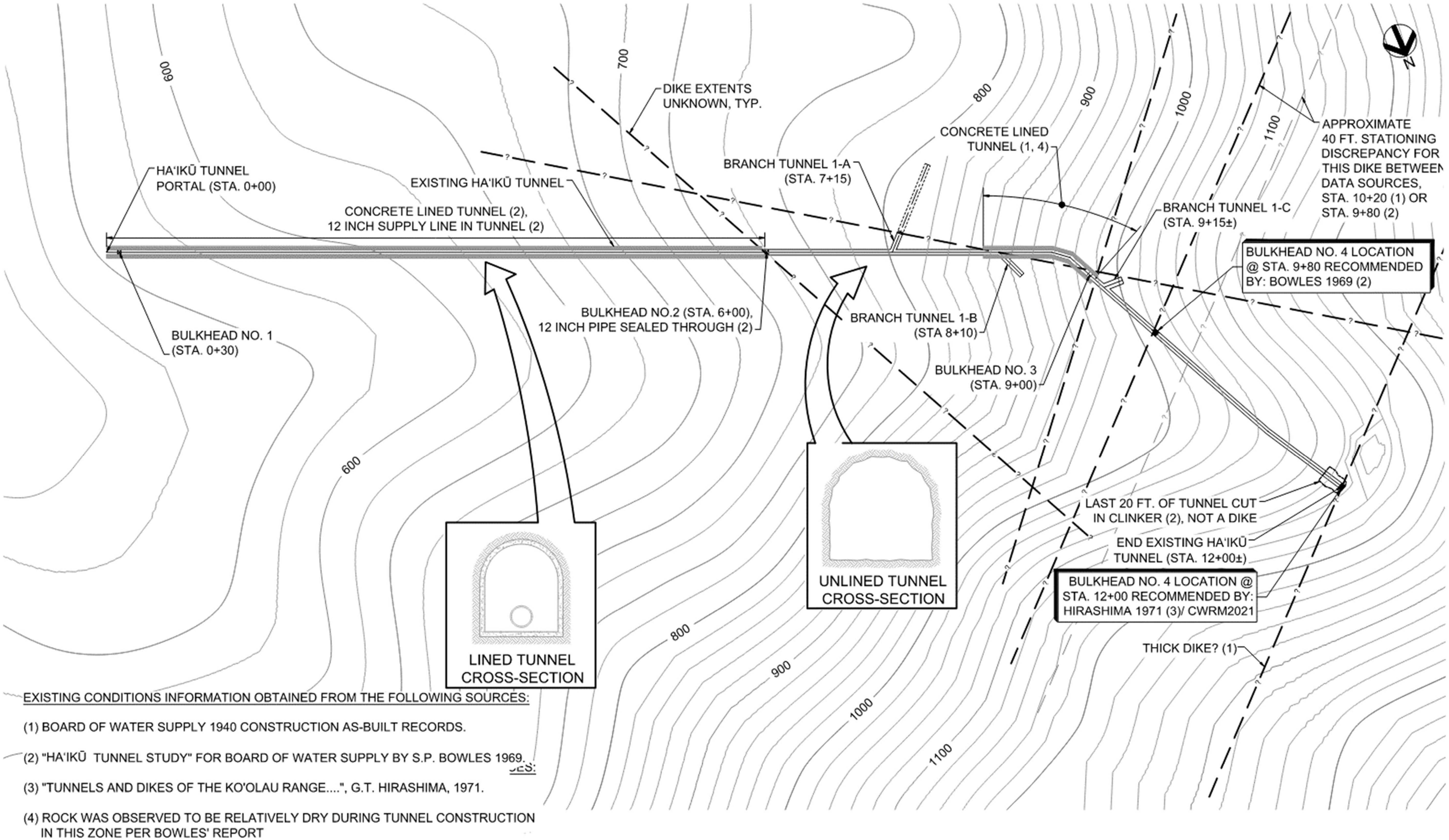

Figure 6: Interpreted tunnel map based on review of historical documentation

Three branch tunnels were mined in an attempt to investigate for the presence of water source compartments. Branch Tunnel 1-A penetrated through the same oblique dike discussed above and into the dry rock. This tunnel was subsequently bulkheaded at the dike to mitigate potential of water loss from the tunnel into the likely "dry" formation. Branch Tunnel 1-B, located approximately 100-feet up-station of Branch Tunnel 1-A, was excavated in the opposing direction from Branch Tunnel 1-A. It was likely used to assist the construction team in understanding the hydrogeologic aspects of the ground and helped guide them into making the decision to change direction of the main tunnel or to investigate for the presence of potential additional water source(s).

Branch tunnel 1-C was constructed at approximately STA 9+15 and was excavated towards the oblique dike previously encountered at STA 7+80 and STA 9+00. It is not clear why this branch tunnel was constructed but was most likely used as an exploratory adit to confirm the orientation and direction of the oblique dike to ensure the main tunnel did not a cross it into a potentially "dry" compartment.

All reference documents listed above show the presence of a 3.5-feet thick dike beyond Bulkhead No. 3. Figure 7 below presents a photo from Bowles' report and shows the dike reported at STA 9+80. The documents prepared by Bowles as well as the 1966 map, refer to Figure 8, indicate that this dike is located at STA 9+80, whereas Figure 9, the "N-00805" map, dated 1940, illustrates it at approximately STA 10+20. Given that the more recent map by Bowles (1969) was developed based on observations from a physical inspection, it is more probable this dike is located at STA 9+80.

Figure 7: "View looking towards portal at about 1000-feet in Ha'ikū Tunnel showing saturated rock in foreground and dike at STA 9+80". (Bowles, 1969)

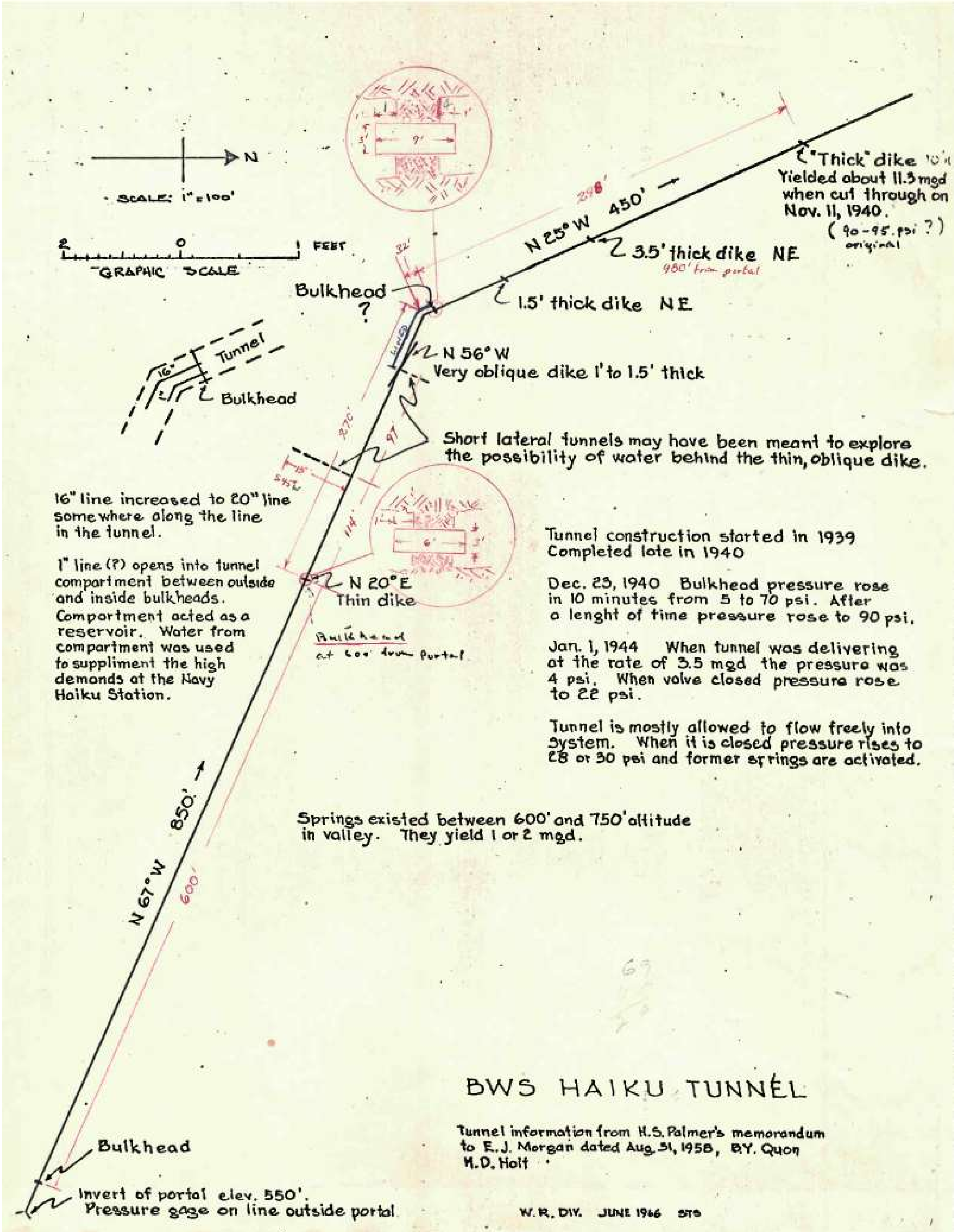

Figure 8: "Haiku Tunnel Study bkg tunnel map 1966"

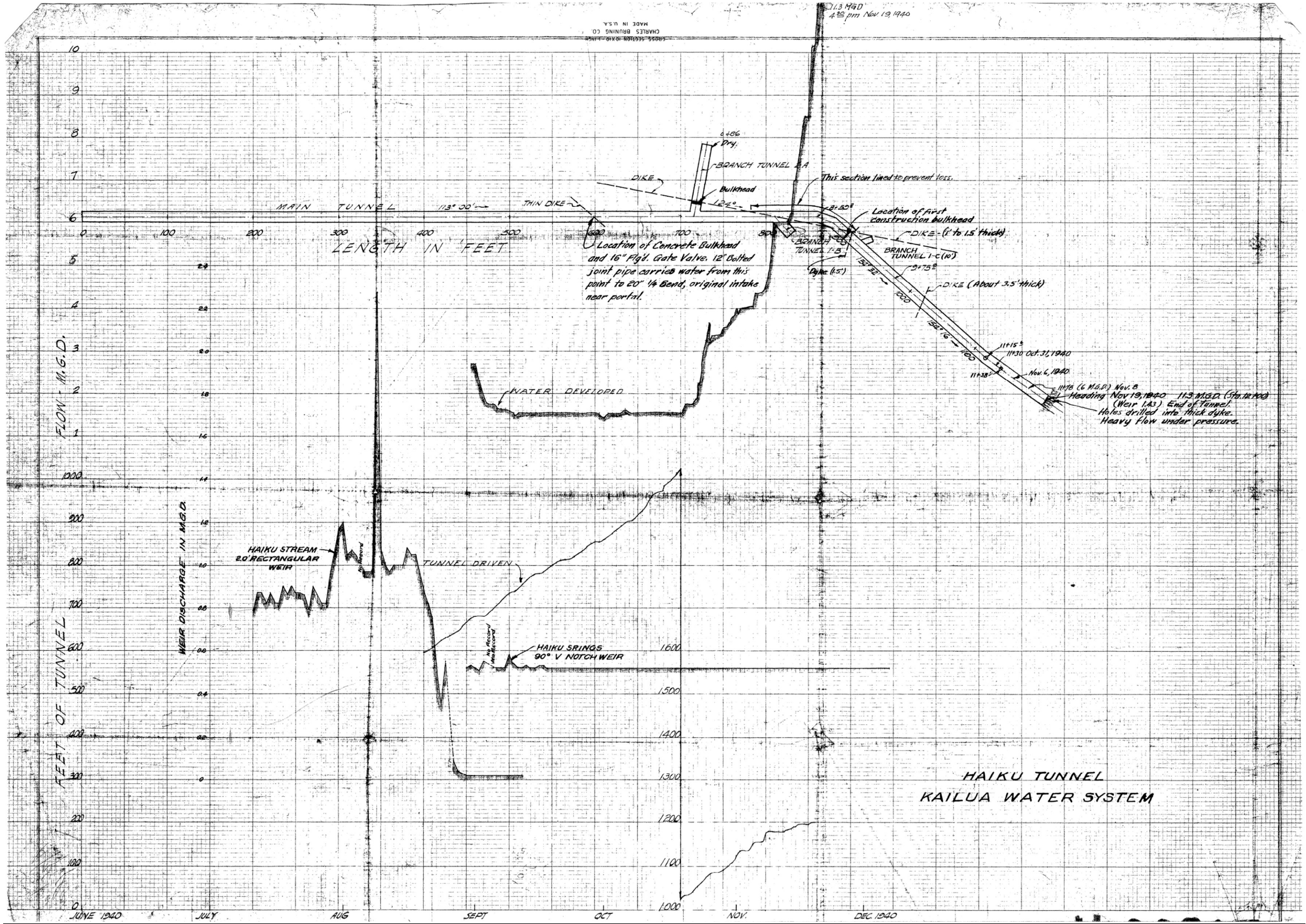

Figure 9: Excerpt from N-00805 PDF – construction record of Ha'ikū Tunnel (circa 1940)

1.2.2 Groundwater Infiltration

The infiltration chart provided on as built drawing "N-00805", presented in Figure 9, indicates that approximately 1.5 MGD was developed by the tunnel prior to STA 9+80 and increased to about 6 MGD up to STA 11+78, then nearly doubled to 11.3 MGD over the last 20-feet of tunnel. Bowles reports that personnel from the HBWS Hydrology and Geology Section had taken measurements from within the tunnel that indicated 97 percent of the infiltration is developed beyond STA 9+50 and that 55 percent of the developed water came from the last 50-feet of tunnel (STA 11+50 to STA 12+00).

Further review of the original construction as-built documentation, circa 1940, notes at STA 12+00 "holes drilled into thick dyke, heavy flow under pressure", leading to the conclusion that the tunnel penetrated several dike compartments in this portion of the tunnel. This is also the same location as recommended by Hirashima's 1971 paper "Tunnels and Dikes of the Koolau Range…"

The assessment and conclusions made by Hirashima and CWRM recommend that a new bulkhead be constructed near the end of the tunnel ~STA 11+80 based on the assumption that a thick dike is present. However, the Bowles report contradicts this and states:

> "*A dike was originally reported at this point, however the recent study found a dense aa flow crosses the tunnel at a slight dip"* and *"The last 20 feet of tunnel is cut in clinker*. *Apparently, the sudden contrast in permeability and rapid increase in flow gave the impression that a dike compartment had been tapped."*

As Bowles physically entered the tunnel and directly observed the conditions inside, and Hirashima did not, Bowles' statements must be given significant consideration. Figure 10 below presents a photograph from Bowles' inspection report. As seen in the image, Bowles is near the end of the tunnel, note that the term heading is used, where infiltration is the greatest. It is noteworthy that Bowles' photo-documented the occurrence of clinker and drill holes where a majority of water discharge was from drill holes in the clinker.

It should be noted that the section of tunnel between Bulkhead No. 1 and Bulkhead No. 2 was concrete lined to function as a groundwater conveyance and mitigate water loss between Bulkheads No. 1 and No. 2. During initial operation and testing it was found that the lined section experienced significant leakage through this liner which led to the installation of a 12-inch diameter conveyance piping from the portal to Bulkhead No. 2 to mitigate water loss through this section of tunnel.

A key component to understanding the operational characteristics of the tunnel was to determine which bulkheads were sealed, and along which lengths of tunnel water is being withdrawn from. As previously noted, the reference documents indicate that piping was installed from the portal to Bulkhead No. 2 and that the bulkhead is sealed. However, it is unclear how well Bulkhead No. 2 is sealed at the interface with the surrounding rock to prevent leakage.

Figure 10: "View of Ha'ikū Tunnel heading, majority of discharge is from drill holes in clinker" (Photograph from Bowles, 1969)

As part of the provided as built information there is no indication that piping was installed beyond Bulkhead No. 2, however, in Bowles' planning document he specifically questions whether or not the piping extends beyond Bulkhead No. 2 as seen in screen-shot of a sketch from Bowles' planning document presented in Figure 11. In Bowles' report, the removal and reinstallation of the 12-inch pipe that extends from the portal through Bulkhead No. 2 is specifically discussed, however, the final report is silent on the presence or absence of piping between Bulkhead No. 2 and Bulkhead No. 3.

The questioning represented in Figure 11 would suggest Bowles would have reported the presence of piping beyond Bulkhead No 2, its removal, and its reinstallation after the inspection. Since there is no discussion of additional piping, it leads the reader to believe that piping between Bulkhead No. 2 and Bulkhead No. 3 did not exist. Lastly, Figure 9 also notes Bulkhead No. 3 as "the first construction bulkhead", raising the question that its purpose might be different than Bulkhead No. 1 and Bulkhead No. 2 which were constructed to prevent water leakage into "dry compartments."

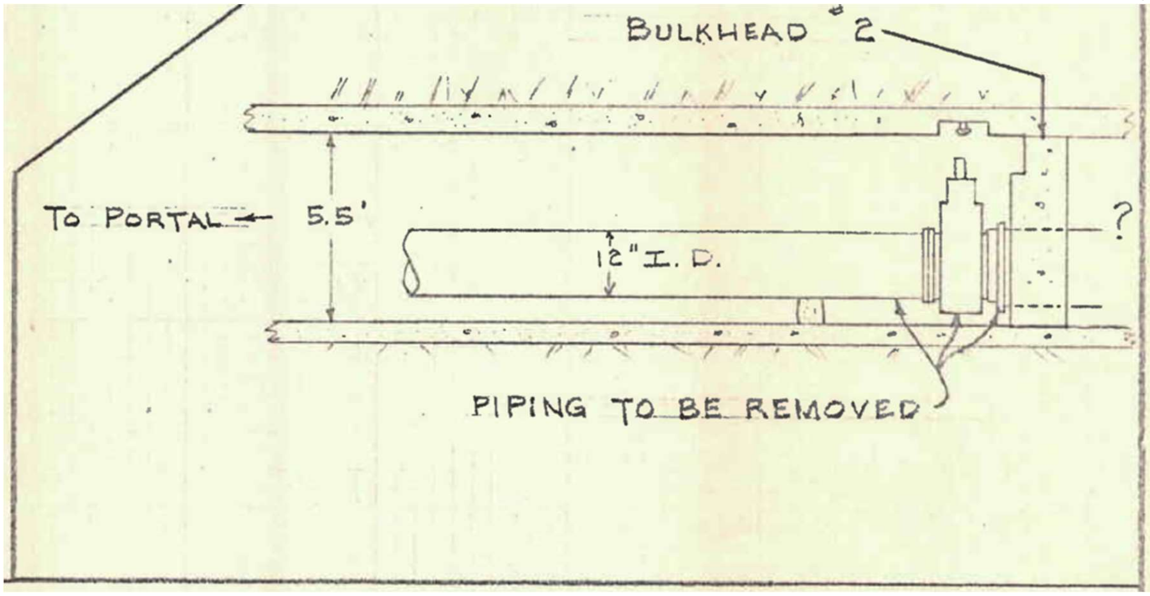

Figure 11: Excerpt from "Planning for Haiku Tunnel Study – Bowles 1969"

To further investigate the purpose of Bulkhead No. 3, the locations where pressure measurements are currently being taken were reviewed. The 1969 field sketch by Bowles has a note that documents the location of the ¼ inch diameter plastic tubing as shown in Figure 12. It states that this tubing was installed to a distance of 50-feet beyond Bulkhead No. 2, which would place it at approximately STA 6+50. Given that pressure measurements are included, it would appear that this tubing is to facilitate the instrumentation. This leads to the conclusion that the measured pressure is representative of that at STA 6+50, which is within the dike compartment located between Bulkhead No. 2 and Bulkhead No. 3.

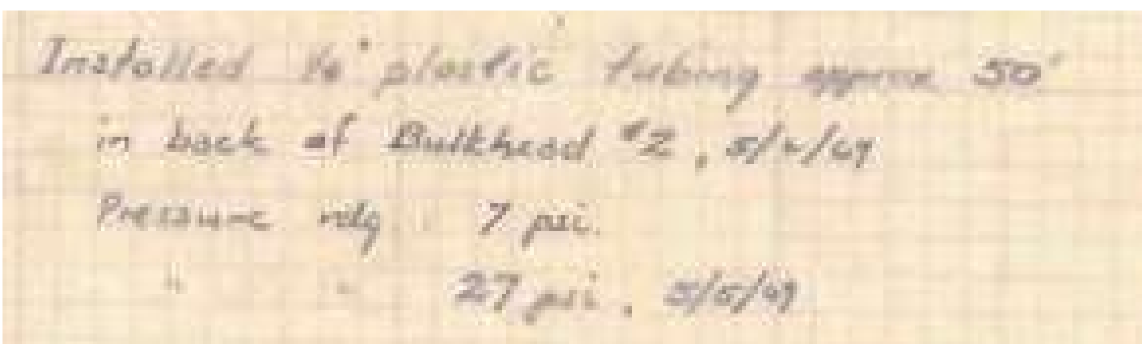

Figure 12: Excerpt from "Ha'ikū Tunnel Study field sketch map 1969"

As Brierley understands, this pressure sensor was used to evaluate the effect of discharge rate on the water pressure within the tunnel, to relate the pressure within the tunnel to the re-activation of natural springs feeding the He'eia Stream, and potentially to relate tunnel pressure to available storage. With this information and understanding of the instrumentation uses, it would lead to the conclusion that piping is unlikely to extend to Bulkhead No. 3, because if it did, the section of tunnel where the pressure sensor is located would be more or less hydraulically isolated from the location where water withdrawal occurs and, therefore, would not be directly affected by discharge from the tunnel.

The only contrary evidence to the location of the pressure sensor and the presence of piping between Bulkhead No. 2 and Bulkhead No. 3 was found in the document titled "Haiku Tunnel Study bkg tunnel map 1966." This schematic shows a 16-inch and a 1-inch line passing through a bulkhead immediately beyond a tunnel bend, refer to Figure 8. Based on a bend being illustrated immediately prior to the bulkhead on this drawing it would seem to indicate that this is Bulkhead No. 3. Additionally, it would seem to be appropriate that anywhere a bulkhead is present that piping is extended to it as to not hydraulically connect compartments. Therefore, it is plausible that piping did exist prior to Bowles' entry into the tunnel but was never reinstalled. The 1966 map, Figure 8, also noted a 1-inch pipe passing through the same bulkhead, presumably Bulkhead No. 3, as follows:

> *"1" line (?) opens into tunnel compartment between outside and inside bulkheads. Compartment acted as a reservoir. Water from compartment was used to supplement the high demands at the navy Haiku Station."*

In our opinion, the level of detail in this note raises questions as to the likelihood that piping was extended to Bulkhead No. 3 after construction. Because this map was developed based on information in an unverified 1958 memorandum, conclusions drawn from the information in Bowles inspection report (Bowles, 1969) are likely more accurate. Lastly, the notation of a 16-inch line may be a misconception about size from the "16" Flg'd Gate Valve" noted in the construction record, as the same note indicates a "12" Bolted joint pipe". Similarly, the noted increase to a 20-inch diameter line may in fact be the "20" ¼ bend" near the portal noted in the construction record.

Bowles' report noted that after construction of Ha'ikū Tunnel, a pressure of 90 to 95 psi was recorded, however, it was not indicated where and how that pressure was measured. It is presumed that the pressure was measured within the pipeline at or outside the portal. This pressure was also reported as a note on the 1966 background map. The 1966 background map, Figure 8, provides a bit more detail on the development of pressure following construction. That map includes four notes with respect to tunnel pressure and withdrawal rates as follows:

> *"Dec. 23, 1940 Bulkhead pressure rose in 10 minutes from 5 psi to 70 psi. After a length of time pressure rose to 90 psi."*
>
> *"Jan. 1, 1944 When the tunnel was delivering 3.5 mgd the pressure was 4 psi. When valve closed pressure rose to 22 psi."*
>
> *"Tunnel is mostly allowed to flow freely into the system. When it is closed pressure rises to 28 or 30 psi and former springs are activated."*
>
> *"Springs existed between 600' and 750' altitude in valley. They yield 1 or 2 mgd."*

Most of these statements have been corroborated by Bowles. Bowles reported that when the pressure sensors in the tunnel, installed behind Bulkhead No. 2, reached a pressure of 20 to 25 psi the stream began to flow similarly to the reported flow measurements taken in 1938, refer to Table 2 below. Table 2 indicates that the stream began to flow somewhere in the vicinity of elevation 682-feet, or higher. Based on the measurements it does not appear that the stream was gaining between elevation 650-feet and 460-feet, note that the tunnel portal elevation is at EL 550-ft. However, the stream was gaining between elevation 460-feet and 272-feet, which was the old station site at approximately the same elevation as USGS stream gauge 16275000.

The 1938 He'eia stream flow data has been confirmed to have been originally published by USGS (Paulson, 1941).

Table 2: Measured He'eia Stream flow on September 21, 1938, as reported by USGS (Paulson, 1941)

Station	Elevation (ft)	Stream Flow (MGD)
1	682	0.228
2	654	1.10
3	616	0.918
4	547	1.18
5	460	1.16
6	446	1.84
Old Station Site	~272	2.28

Bowles concludes his 1969 study by recommending that a 4th bulkhead be installed at STA 9+80, which is the furthest up-station dike location observed during the inspection. Based on the provided information we infer that Bulkhead No. 3 is likely not sealed, that the tunnel extends through only one dike up-station from Bulkhead No. 3, and that the subject dike is located at STA 9+80. Bowles also suggested that the tunnel be extended or that additional holes be horizontally drilled at the heading to increase the withdrawal rate of water from the clinker into the tunnel.

Figure 13 illustrates the most probable dike compartments penetrated by the Ha'ikū Tunnel. As interpreted from the information sources cited in this report, there are likely three water storage compartments between:

- STA 6+00 and STA 9+00,
- STA 9+00 and STA 9+80,
- and the compartment that begins at STA 9+80 extends beyond the length of the excavated tunnel.

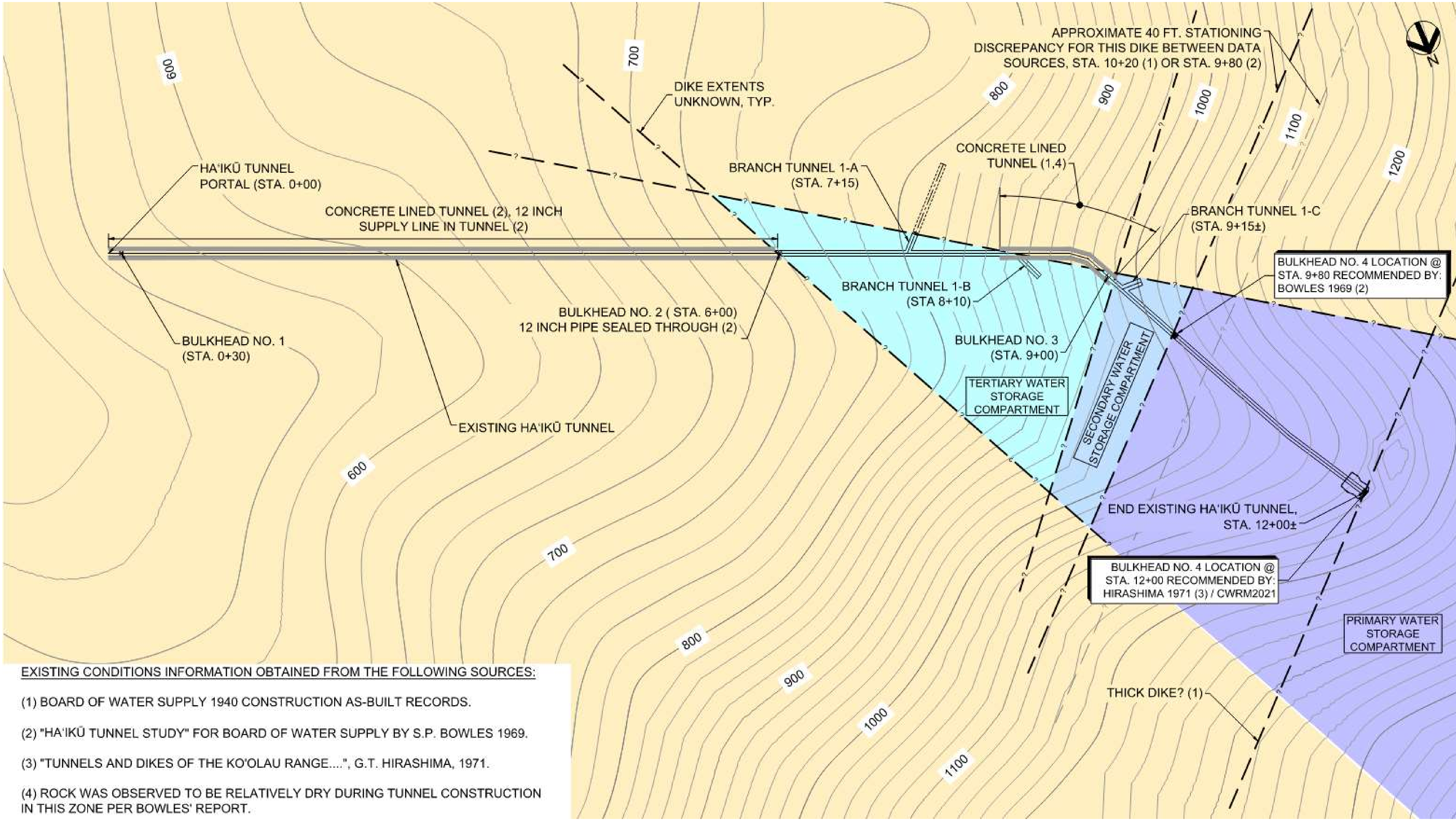

Figure 13: Theorized water storage compartments

1.3 Summary

- Ha'ikū Tunnel construction commenced in 1939 and was completed in late 1940. The tunnel extends approximately 1200-feet with 3 bulkheads installed along its length. According to the historical information three branch tunnels were excavated in attempt to reach perceived and/or investigate potential water source(s).

- The unpublished 1969 inspection by Stephen P. Bowles of the HBWS Hydrology & Geology Section, Planning, Resources & Research Division (Bowles, 1969) provided field and background maps that indicated Bulkhead No. 1 was installed near the portal at STA. 0+30, Bulkhead No. 2 was installed at STA 6+00, at the first known dike crossing which has a reported thickness of 1.5-feet, and Bulkhead No.3 was installed at STA 9+00.

- The infiltration chart provided on as built drawing "N-00805", presented in Figure 9, indicates that approximately 1.5 MGD was developed by the tunnel prior to STA 9+80 and increased to about 6 MGD up to STA 11+78, then nearly doubled to 11.3 MGD over the last 20-feet of tunnel.

- The assessment and conclusions made by Hirashima and CWRM recommend that a new bulkhead be constructed near the end of the tunnel ~STA 11+80 based on the assumption that a thick dike is present. However, the Bowles report contradicts the assumption that led to Hirashima's and CWRM's conclusions. Bowles states:

  > *"A dike was originally reported at this point, however the recent study found a dense aa flow crosses the tunnel at a slight dip" and "The last 20 feet of tunnel is cut in clinker. Apparently, the sudden contrast in permeability and rapid increase in flow gave the impression that a dike compartment had been tapped."*

- Bowles' report noted that after construction of Ha'ikū Tunnel, a pressure of 90 to 95 psi was recorded and that when the pressure sensors in the tunnel, installed behind Bulkhead No. 2 reached a pressure of 20 to 25 psi, the stream began to flow similarly to the reported flow measurements taken in 1938.

- Bowles concludes his 1969 study by recommending that a 4th bulkhead be installed at 9+80 which is the furthest up-station dike location observed during the inspection. Bowles also recommends that the tunnel be extended or that additional holes be horizontally drilled at the heading to increase the flow rate of water from the clinker into the tunnel.

- Based on the provided information we infer that Bulkhead No. 3 is likely open and the tunnel extends through only one dike up-station from Bulkhead No. 3, which is located at STA 9+80.

- As interpreted from the information sources cited in this report, there are likely three water storage compartments:

1. between STA 6+00 and STA 9+00,
2. between STA 9+00 and STA 9+80, and
3. beginning at STA 9+80 extending beyond the length of the excavated tunnel.

2 EXISTING HYDROGEOLOGICAL CONDITION

2.1 Existing Condition Analysis

As described above, the water source compartments are developed by vertical dikes extending up through the basalt rock mass. Water is stored within the porous rock mass and the tunnel functions as a horizontal well puncturing through the dikes into each of the storage compartments. Figure 14 depicts how the dikes extend vertically up to, or nearly up to, the ground surface, and therefore the height of the storage compartments can likely be related to the ground surface elevation.

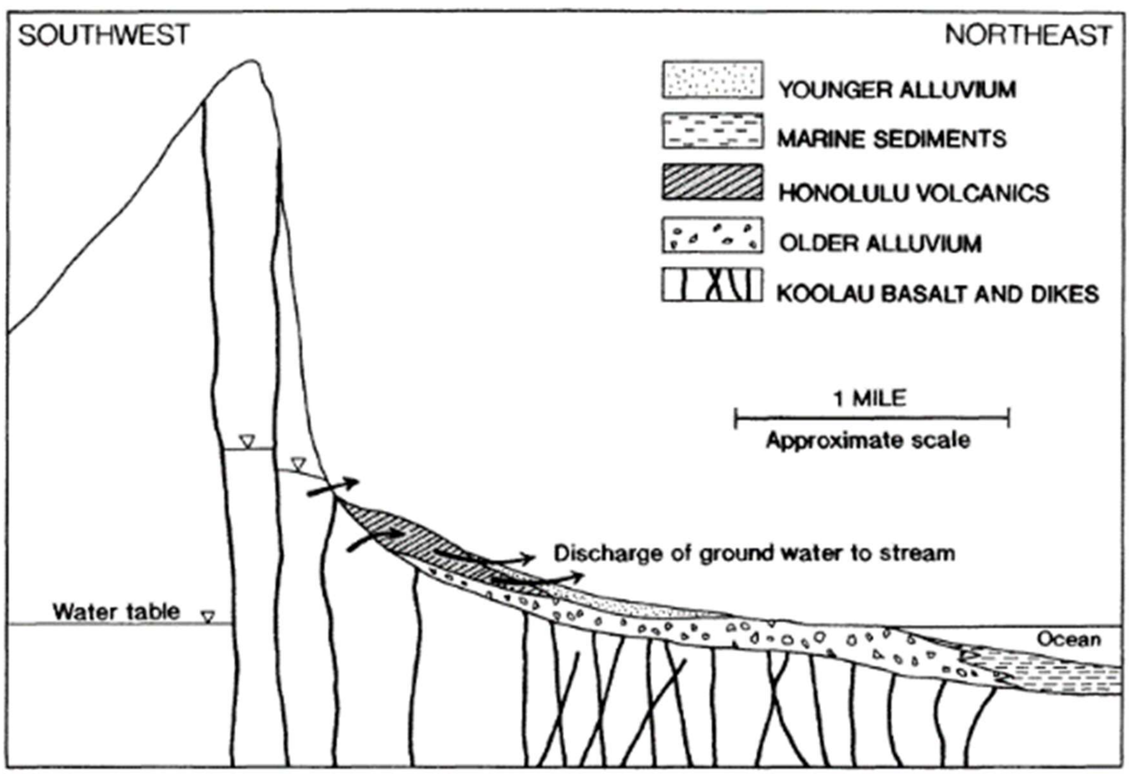

Figure 14: Illustration depicting dikes and water storage compartments within the Ha'ikū Valley (From Takasaki and Mink, 1985)

As noted in the previous section, the available information appears to indicate that a dike is located at Bulkhead No. 3 and that Bulkhead No. 3 has an open 9-foot section of 36-inch diameter pipe passing through it. If this is true, then the two dike compartments up-station are constantly supplying water to the compartment between Bulkhead No. 3 and Bulkhead No. 2. Furthermore, based on the elevations of the reported activated springs supplying water to the He'eia Stream, it is likely that those springs are fed by the compartments down station from Bulkhead No. 3, refer to Figure 15 below for depiction of the dike locations and potential compartments developed by the dikes. This profile illustrates the ground and stream elevation along the length of the Ha'ikū Tunnel.

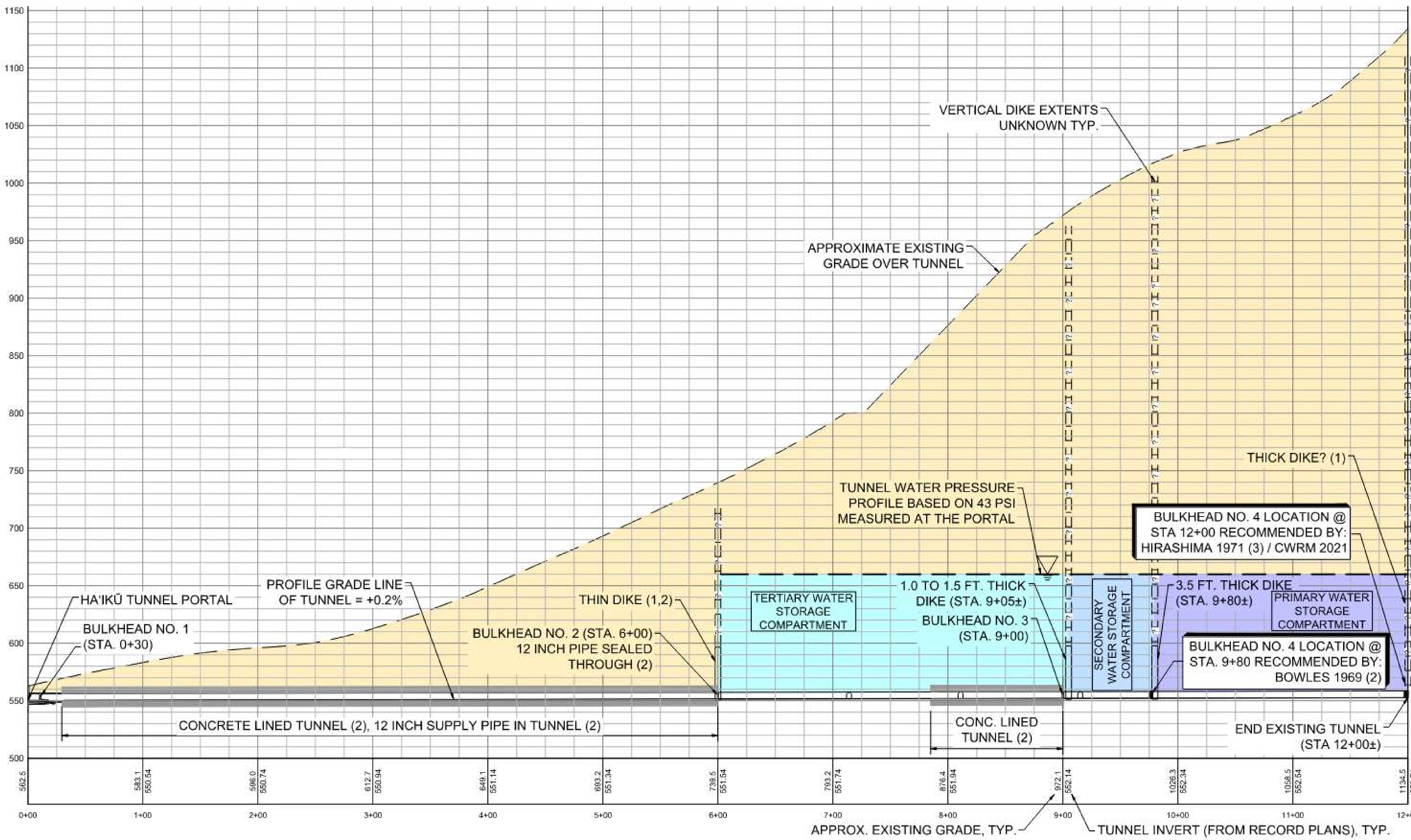

Figure 15: Profile of the Ha'ikū Tunnel – developed from Bowles' report

2.2 Review of Historical Streamflow, Rainfall and Tunnel Operation Data

Historically, flow in the He'eia Stream has been monitored at USGS stream gauge 16275000 (elevation 272 feet MSL). More recently, between August 25, 2021 and March 9, 2023, a second stream gauge, USGS 16274950, was installed to monitor stream flow upstream and nearer the tunnel. USGS stream gauge 16274950 is located downstream of the tunnel portal at approximately elevation 460 feet MSL. The locations of both USGS stream gauges are shown below in Figure 16.

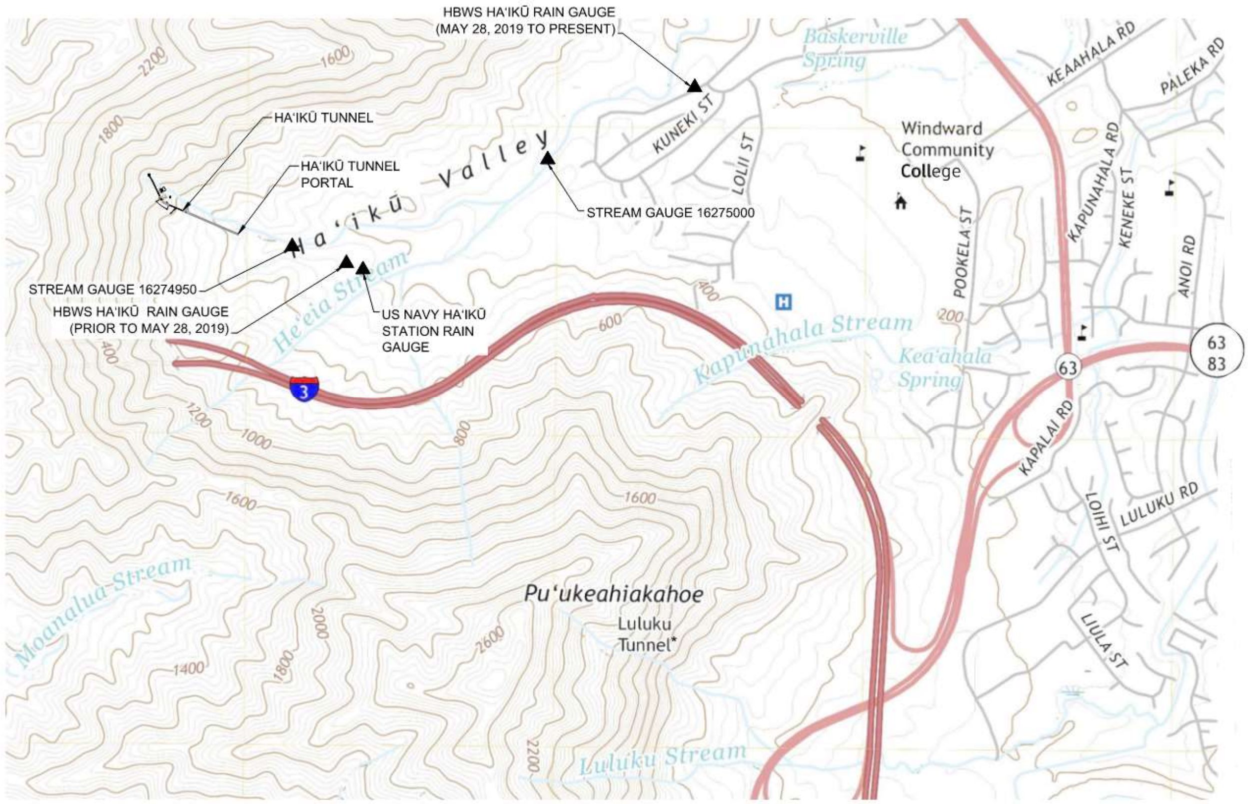

Figure 16: Location map of Ha'ikū Tunnel, He'eia Stream and relevant USGS stream gauges

For purposes of illustrating the effect of the tunnel connecting the intercepted dike compartments, assuming an open Bulkhead No. 3 and no Bulkhead at the dike located at STA 9+80, inferred groundwater levels have been drawn as shown on Figure 15. Note that the groundwater levels have a high degree of uncertainty, as the only known groundwater pressure measurement is by the sensor located on the pipeline at the tunnel portal. A maximum pressure of 47 psi at this location was observed when water was not being extracted from the Ha'ikū Tunnel between October 2021 and April 2022 as indicated in the data provided by the HBWS. The plots provided in Figure 17 presents this data. This groundwater pressure of 47 psi is equivalent to a height of water of about 108-feet, corresponding to EL 660-feet at that location. Since April 2022, the withdrawal rate has been steady at 0.35 MGD and monitoring at the portal has indicated a relatively steady groundwater pressure of 43 psi, which is equivalent to a height of water of about 99-feet, corresponding to about EL 650-feet at that location.

Figure 18 shows the available stream flow data recorded at USGS 16275000 and 16274950 during the time period between August 25, 2021 and May 3, 2023. Stream flow at USGS 16274950 is typically about 60% to 70% of flow measured at USGS 16275000 indicating that the stream is gaining between these two locations, however, over some time intervals it is nearly 100% of the flow recorded at USGS 16275000. Where measurements are at or nearly at 100%, the validity of the measurements is questionable as it is known to HBWS personnel that human activity in the vicinity of the gauge stations occurs from time to time that includes damming up the stream to create swimming holes. The damming artificially raises the water at the gauge location giving the appearance of higher flows. It is also noted that a confluence occurs between the two stream gauges, however, based on discussions with HBWS employees and information provided in USGS Report 92-4168 (Izuka et. al., 1993) the other streams are intermittent and only flow during and immediately after rain events. That USGS report also indicates that stream flow was monitored on four occasions between November 6th and December 20th, 1991, at various locations along the stream. The highest monitoring point was just above the tunnel portal elevation and the lowest point was downstream from USGS 16275000 near the Kahekili Highway. This monitoring showed that the stream is gaining over that stretch of stream and that the stream gained by 20% to 60% between the approximate elevation of USGS 16274950 and USGS 16275000, this finding is similar to the more recent data shown in Figure 18.

The stream flow data presented in Figure 19 covers the time period from August 25,1981 through March 9, 2023 and shows available stream flow data at both stream gauging stations, withdrawal rates from the Ha'ikū Tunnel and Well, and available rainfall data from the HBWS rain gauge station. The fluctuation in flow appears to be consistent at each station providing significant evidence that the water withdrawal rates from the Ha'ikū Tunnel had negligeable effect on stream flow during this timeframe that is more than 40 years. Whereas the stream flows seem to be predominantly affected by rainfall as would be expected.

Seepage runs performed in November and December of 1991 indicate that flow in the stream was beginning near the tunnel portal elevation, 550-feet, and increased to about 0.86 MGD near elevation 450-feet. This data suggests a reduction in base flow at tunnel elevation, which is likely caused by the tunnel presence. More importantly, it suggests that the groundwater in the dike compartments have been depressed and higher elevation springs have been deactivated. Given that this data only captures a comparison between two snapshots in time, additional seepage runs are warranted to assess spring activation relative to stream elevation. It is also important to evaluate total rainfall in the area leading up to the monitoring or seepage runs to understand if those runs were taken after a particularly drier period of time.

Recent measurements at elevation 460, USGS 16274950, show typical flow rates ranging between 0.5 and 1 MGD over the time period between August 25, 2021 and March 9, 2023, refer to Figure 18. However, it should be noted that the reported stream flow data at USGS 16275000 appears to indicate that recent stream flow, between May 2020 and July 2022, is nearer the low range recorded over the past 40 years. As seen in Figure 19, which covers a much longer timeframe than what is shown in Figure 18, He'eia Stream average flow is somewhat cyclical and ranges between 0.6 and 1.5 MGD indicating that the area is in a relatively drier period since May 2020.

Figure 20 presents a plot of the daily average He'eia Stream flow and Ha'ikū Tunnel withdrawal as well as the total rainfall by year. Rainfall data collected at two stations is shown on the plot, both stations were located in close proximity to the tunnel portal and should be reasonably representative of the total rainfall within the Ha'ikū Valley that attributes to groundwater recharge for the Ha’ikū Tunnel. The U.S. Navy Ha’ikū Station was operated between 1952 and 1998 with data available on the Rainfall Atlas of Hawaii Interactive Map by University of Hawaii at Manoa (T.W. Giambelluca et al, 2013) for most years. However, some data was noted to not be of high quality, “unverified,” due to relatively illegible handwriting on the documentation, only one value being present for the entire month, etc. Therefore, two rainfall data sets have been plotted as on the figure, one as “Verified” and the other as “Unverified” so that the data may be distinguished by the reader. The other rain gauge has been operated by HBWS since June 2002. However, only data through 2018 was used as in May 2019 the station was moved to a much lower point in the Ha’ikū Valley and is likely not representative of the rainfall for the drainage basin likely feeding the dike compartments associated with the Ha’ikū Tunnel.

He’eia Stream flow data is available from the USGS website for Stream Gauge 16275000 is available as early as February 1, 1914, however, data is discontinuous and is only available as daily averages prior to October 1990. Refer to Table 3 for a summary the available data from USGS.

Table 3: Time periods of available He’eia Stream flow data at USGS 16275000

Time period	Frequency
February 1914 – September 1919	Daily Mean
July 1939 – November 1977 & September 1982 – September 1990	Daily Mean
October 1990 – Present	5 to 30 minute intervals

Figure 20 also presents the daily average withdrawal from the Ha’ikū Tunnel for each year of available data. Withdrawal rates from the Ha’ikū Tunnel since January 1, 1959 were provided by HWBS. Additional yearly average withdrawal rates were plotted for the time period between 1947 through 1957 and 1960 based on information found in USGS Water-Supply Paper 1894 (Takasaki et al, 1969). Ha’ikū Tunnel withdrawal rates for those years were either back calculated from water budget analyses or directly indicated, refer to Section 2.3 for discussion on the back calculated Ha’ikū Tunnel withdrawal rates. As seen in that plot the average He’eia stream flow is generally between 1 and 2 MGD over the past 40 years with some higher and lower outliers that typically line up with particularly higher or lower than normal total rainfall years.

Pressure monitoring data, as provided by HBWS, reveal that during the tunnel shut down between October 2021 through April 2022 the tunnel reached an internal pressure of about 47 psi. This pressure is lower compared to the 90 psi shut-in pressure reported in December 1940. However, the effects of potentially hydraulically connected tunnels and wells that were installed in Ha’ikū Valley and nearby valleys post-1940, as well as the extended period of drought during 2021 and 2022, likely affected the maximum pressure recorded during the October 2021 to April 2022 Ha’ikū Tunnel shutdown.

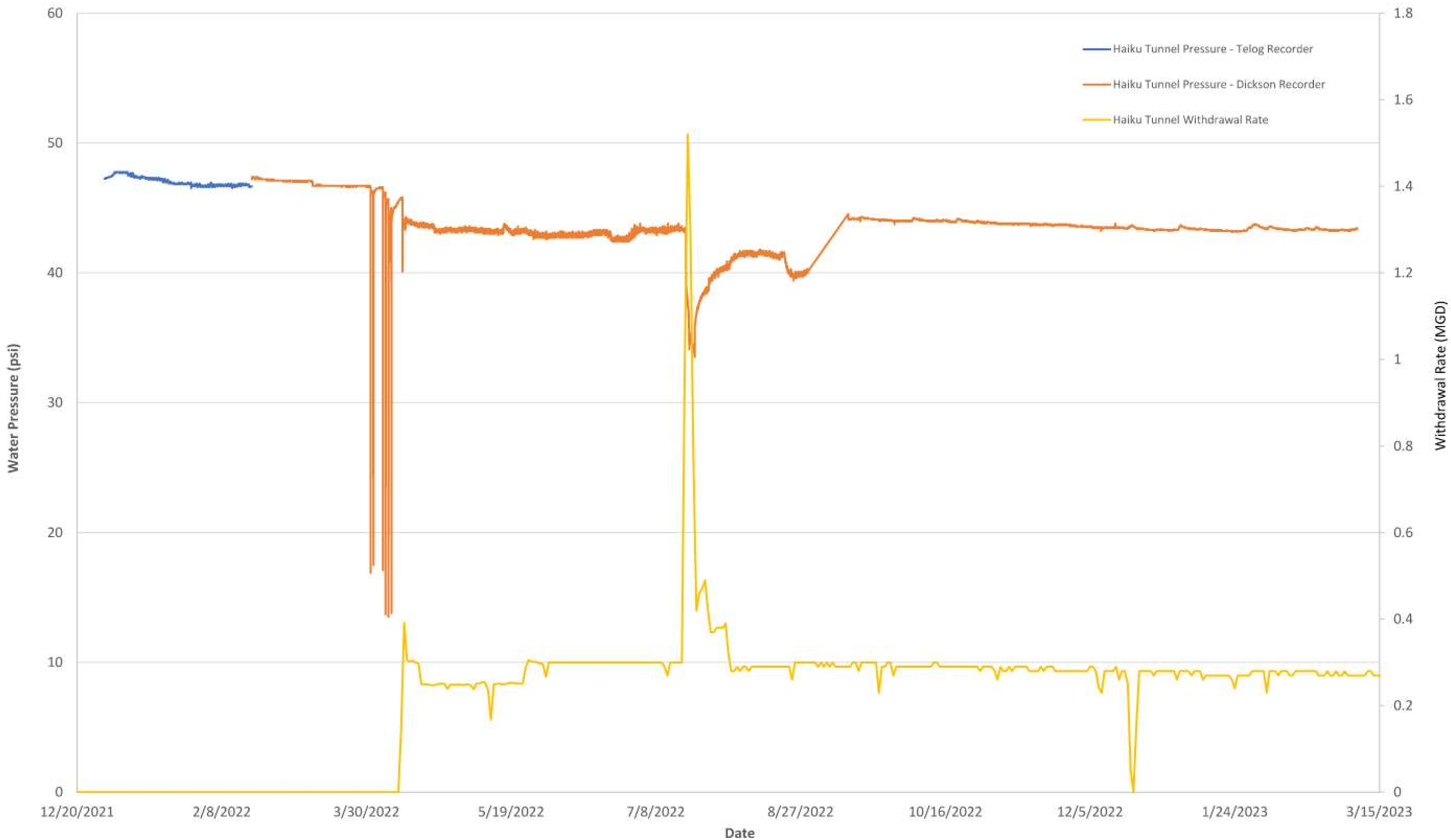

Figure 17: Ha'ikū Tunnel internal pressure data and withdrawal rate

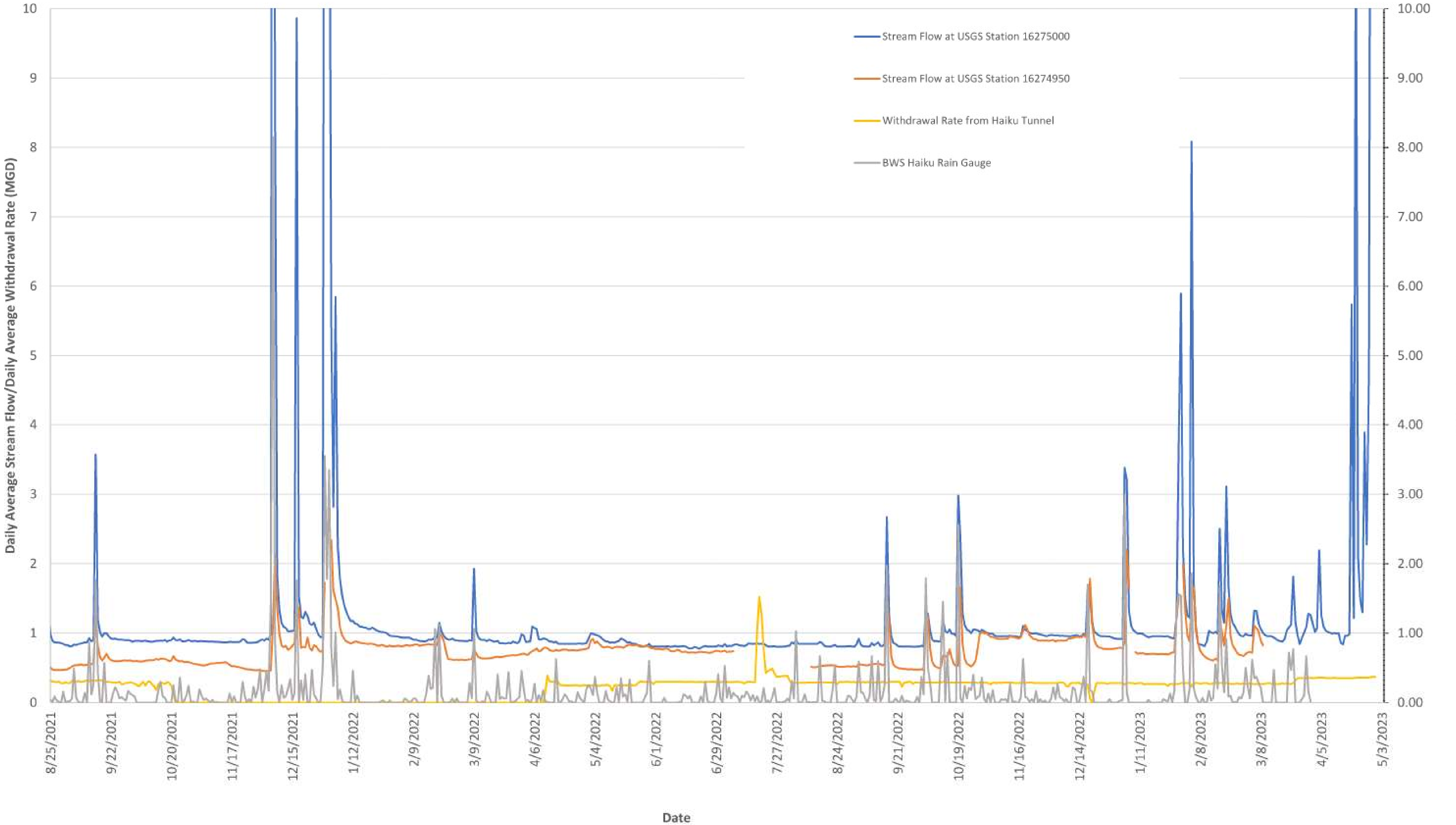

Figure 18: He'eia Stream flow at USGS 16275000 and 16274950, Ha'ikū Tunnel withdrawal rate, and rainfall data (From USGS and HBWS)

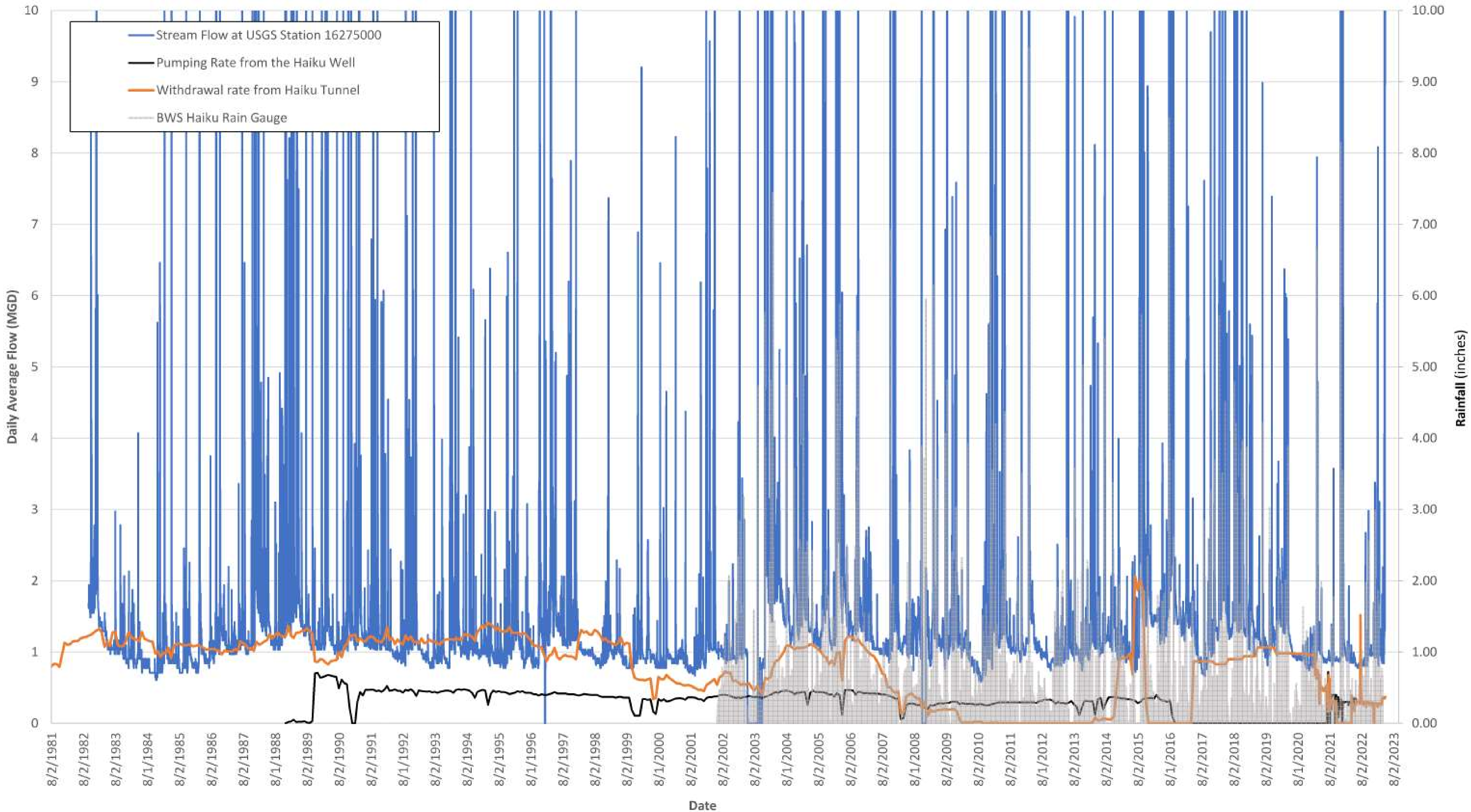

Figure 19: He'eia Stream flow, Ha'ikū Tunnel withdrawal rate, and rainfall data (From USGS and HBWS)

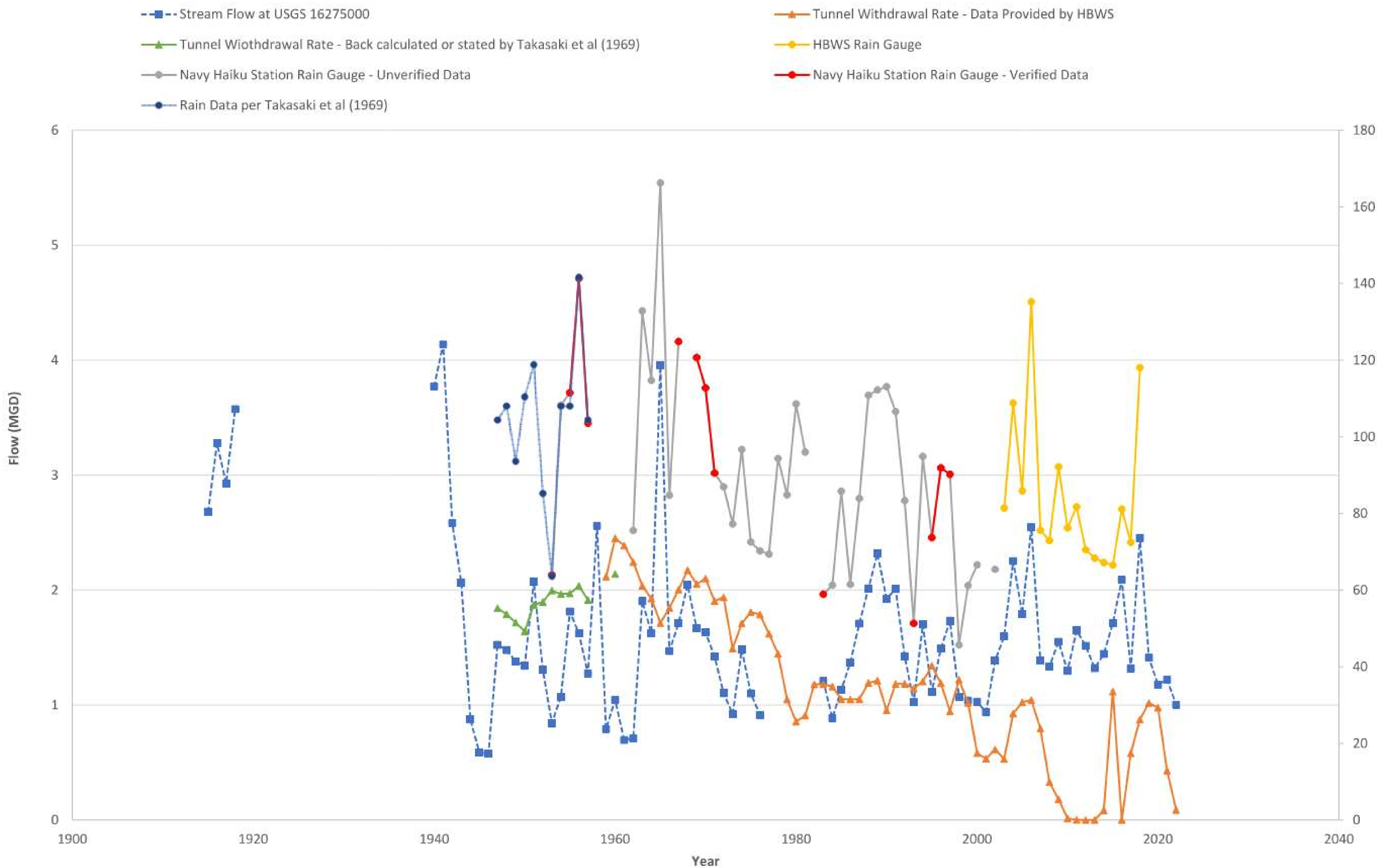

Figure 20: Daily Average He'eia Stream flow and Ha'ikū Tunnel withdrawal rate by year, and total rainfall (From USGS and HBWS)

2.3 Stream Flow Duration Curve Analysis

Flow duration curves are cumulative frequency curves that show the percentage of time a particular flow rate was equaled or exceeded. For this study, discussing flow characteristics and effects on them based on groundwater withdrawal is a more appropriate method than simply looking at mean flow. Flow duration curves provide a method to understand the effect of storm events that can skew comparisons as well as provide a better understanding of stream flow at the extremes. USGS Report 92-4168 "Geohydrology and Possible Transport Routes of Polychlorinated Biphenyls in Ha'ikū Valley, Oahu, Hawaii" (Izuka,et al 1993) presented a plot with three flow duration curves representing distinct time periods associated with groundwater development near the He'eia Stream. That report identified the three data periods as follows:

1. The period before completion of the Haʻikū water Tunnel in 1940,
2. The period between the completion of the water tunnel and the beginning of pumping at well 2450-2 in 1988, and
3. The period after completion of the water tunnel and the beginning of pumping at well 2450-2.

The flow duration curve is presented in USGS Report 92-4168 is shown in Figure 21 below. It is important to note that each of those flow duration curves were generated using data over significantly different time period lengths and that daily water withdrawal rates from the Haʻikū Tunnel are not available prior to January 1, 1981 but date back to 1959 in the form of monthly rates. Other historical documents, as discussed later in this Section, were used to determine yearly average water withdrawal rates from the Haʻikū Tunnel dating back to 1947. Therefore, inferences can be made to assess the effect on the He'eia Stream. Table 4 below presents the durations of collected He'eia Stream flow data, per USGS, for each time period described above.

Table 4: Summary of data utilized to generate flow duration curves presented in USGS Report 92-4168

Time Period	Date Range of Data Utilized
1	5.9 years of data collected from October 1914 to September 1919 combined with 11 months of data collected 20 years later from October 1939 to September 1940
2	35.9 years of data collected from October 1941 to September 1977 combined with 4.9 years of data collected 5 years later from October 1982 to September 1987
3	2 years of data collected between 1989 and 1991

USGS Report 92-4168 states that the flow duration curves show that base flow of the He'eia Stream has decreased after water withdrawal from the Haʻikū Tunnel began in 1941 and increased after withdrawal of water began from the Haʻikū Well in 1989. However, that report further states that it is unclear if the reduction in base flow is due to the withdrawal of water from the tunnel and well or if it is due to climatic variations. Rainfall measurements taken at the Lower Luakaha rain gauge located 6 miles southeast of Haʻikū Valley indicated a total rainfall reduction of about 24% when comparing Time Periods 2 and 3 with Time Period 1 defined above in Table 4. Further analysis of the data by Izuka et al, led to their conclusion "that the tunnel is at least partly responsible for the decrease in base flow of the stream."

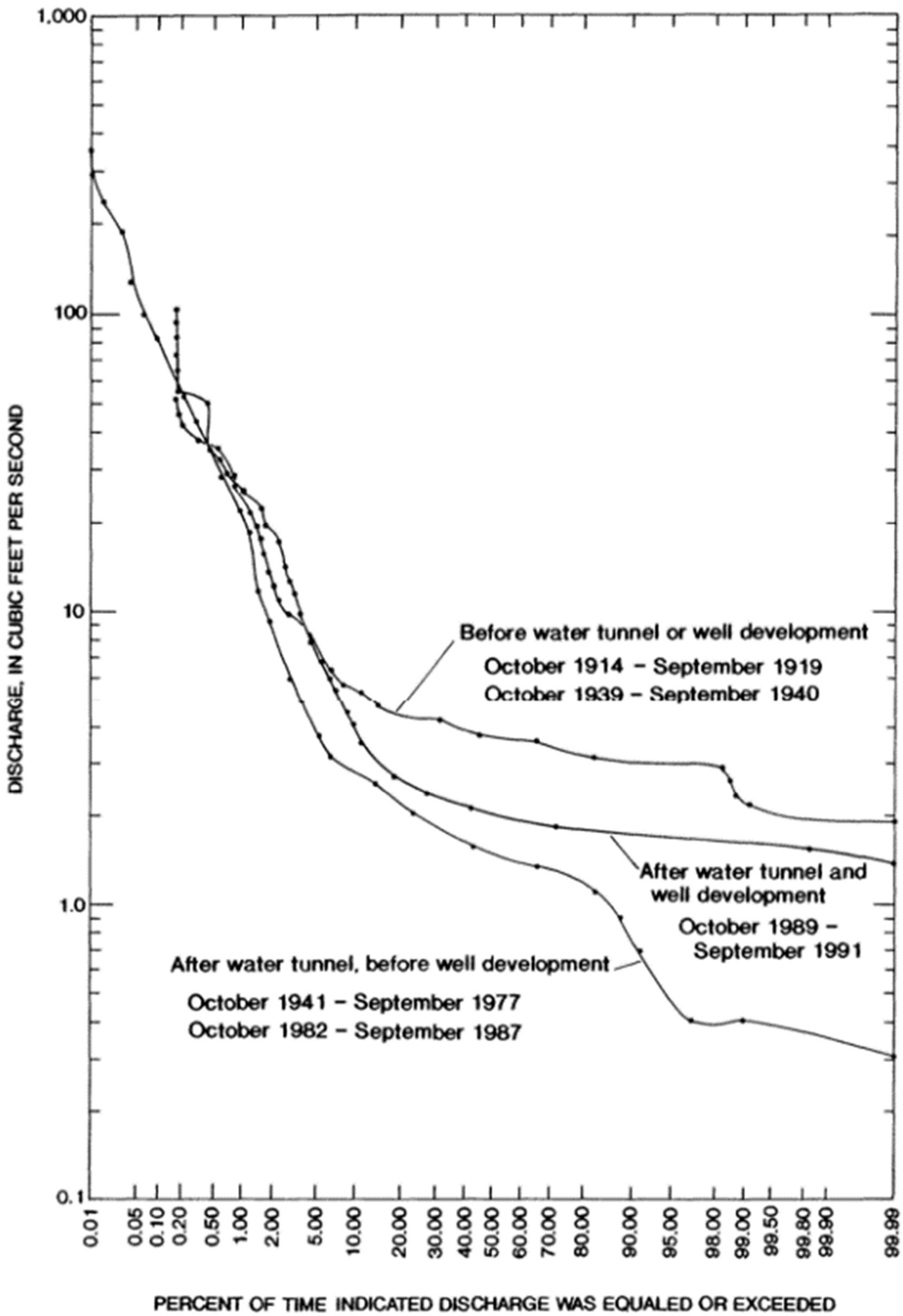

Figure 21: Flow duration curves of daily mean flows based on record for He'eia Stream at USGS 16275000 (Izuka et al, 1993)

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As previously stated, and as seen in Table 4 above, the available data for Time Period 2 is about 6 times the length as compared to Time Period 1 and 20 times the length as compared to Time Period 2. Therefore, fluctuations in rainfall and groundwater usage may not be equally represented across each time period. As part of this study for HBWS, flow duration curves were developed for the He'eia Steam for each year where data is complete. The flow duration curves were developed using available data from the USGS 16275000. Those plots are provided in Appendix B and summarized in Figure 22.

After review of each yearly flow duration curve the following observations have been made:

- It is evident that stream flow reduced after tunnel construction and gradually decreased from 1941 to 1944.
- During 1945 and 1946 a significant reduction in stream flow occurred.
- Between 1947 and 1952 stream flows increased to flows similar to what was observed between 1941 and 1944
- Stream flow significantly decreased between 1953 and 1963 similar to the low flows measured between 1945 and 1946.
- In 1964 stream flows again jumped up to the early 1940, post tunnel construction, stream flows and have been relatively steady with fluctuations appearing to follow total rainfall.
- Since 1964, Q_{90} has generally been between 1.0 MGD and 2.0 MGD

Figure 22 illustrates the flow duration curves over the time periods where yearly curves are similar as described above. For curves post 1964, the data was generally separated into decade intervals.

As part of USGS Water-Supply Paper 1894 (Takasaki et al, 1969), the long-term Q_{90} of the stream was calculated as 1.2 MGD for the base period between 1927 and 1960, which is similar to the Q_{90} values calculated since 1964. However, because only limited stream data prior to construction of the Ha'ikū Tunnel was available that long-term Q_{90} value was based on correlations with the East Branch Manoa Stream. With respect to the validity developing correlations between the He'eia Stream and the East Branch Manoa Stream Takasaki (1969) states:

> *"Although it (East Branch Manoa Stream) is in southern Oahu on the leeward side of the Koolau Range, this stream is hydrologically similar to windward streams, and it has a long continuous record of observation under natural conditions. It therefore provides a better base for comparison than does the record of any stream on the windward side."*

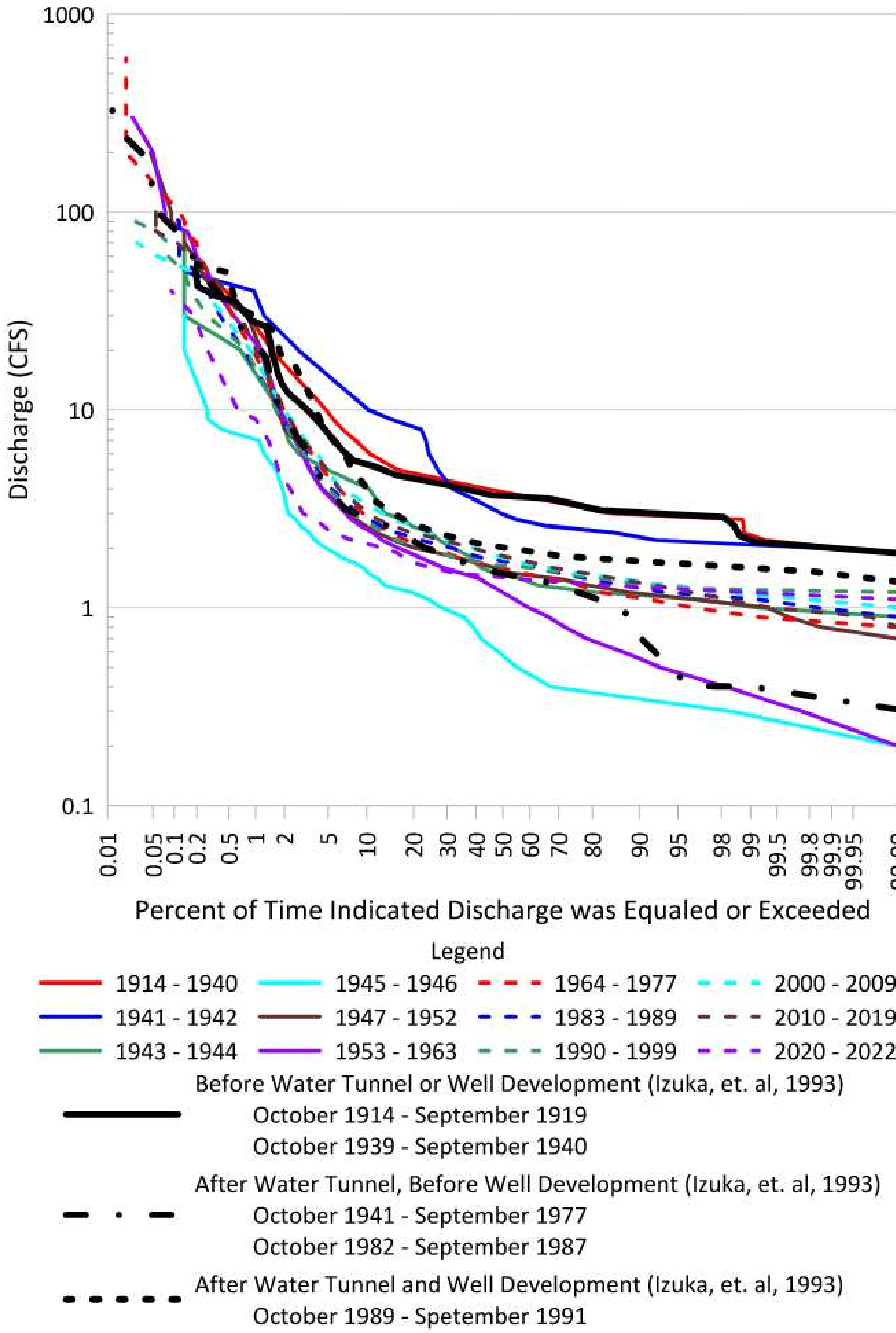


Figure 22: Flow duration curves developed as part of this study for HBWS (Data obtained from USGS)

To understand why stream flows were substantially less in 1945, 1946, and between 1953 and 1963, a historical document review was performed to investigate water withdrawal rates from the Haʻikū Tunnel, as data provided by HBWS is only available dating back to 1959. In USGS Water-Supply Paper 1894 (Takasaki et al, 1969) a prepared water budget of upper Haʻikū Valley is provided in table format for the year 1947 through 1957. That water budget provides the summation of calculated He'eia Stream base flow at USGS 16275000 and water withdrawal from the Haʻikū Tunnel in one column and the surface runoff calculated at USGS 16275000 as shown in Table 5 below. Using that information and daily average stream flow provided by USGS, at the location of that stream gauge, back calculations for water withdrawal from the Haʻikū Tunnel can be performed. Table 6 presents the back calculated yearly average water withdrawal rate from the Haʻikū Tunnel between 1947 and 1956. As seen in this table, the withdrawal rates range between 1.64 and 2.04 MGD, an average of 1.88 MGD, and generally increased over the reported 11-year period. The 1969 report also indicates that the yield (tunnel withdrawal rate) was 2.14 MGD in 1960. It is assumed that this is an average for the year. These tunnel withdrawal rates are included in the plot presented in Figure 20. As seen in that plot; tunnel withdrawal rates were generally above 1.7MGD through the early 1970's and it does not appear that there was significantly less total rainfall for the years where significantly lower stream flow was recorded. Therefore, there were likely other factors that resulted in the low stream flows during that time that are not well understood, such as effects from groundwater withdrawal operations in nearby valleys.

Table 5: Water budget of upper Ha'ikū Valley, 1947 to 1957 (Takasaki et al, 1969)

Year	Rain		Base flow [1]	Storm runoff	Water yield	Difference
	Feet	Acre-Feet	Acre-Feet	Acre-Feet	Acre-Feet	Acre-Feet
	a	b	c	d	c+d	b-(c+d)
1947	8.7	5380	3140	630	3770	1610
1948	9.0	5590	3220	450	3670	1920
1949	7.8	4850	2960	510	3470	1380
1950	9.2	5730	2820	520	3340	2390
1951	9.9	6130	3430	990	4420	1710
1952	7.1	4430	3290	310	3600	830
1953	5.3	3300	3090	90	3180	120
1954	9.0	5590	2910	490	3400	2190
1955	9.0	5590	3210	1030	4240	1350
1956	11.8	7330	3420	690	4110	3220
1957	8.7	5390	2900	670	3570	1820
Total	95.5	59310	34390	6380	40770	18540
Mean	8.7	5390	3130	580	3710	1680
	(104 inches)	(4.8 mgd)	(2.8 mgd)	(0.5 mgd)	(3.3 mgd)	(1.5 mgd)

[1] Sum of measured Haiku
and computed groundwater increment of streamflow at gauging station.

Drainage area - 621 acres (0.97 sq mi.); gaging station, alt 272 ft; Haiku tunnel, alt 550 ft

Table 6: Yearly average groundwater withdrawal rate from the Haʻikū Tunnel

Year	Tunnel Withdrawal Rate (MGD)	Year	Tunnel Withdrawal Rate (MGD)
1947[1]	1.84	1953[1]	2
1948[1]	1.79	1954[1]	1.97
1949[1]	1.72	1955[1]	1.97
1950[1]	1.64	1956[1]	2.04
1951[1]	1.87	1957[1]	1.91
1952[1]	1.90	1960[2]	2.14

[1] – average tunnel flow back calculated from Takasaki et al (1969)

[2] – yield provided for 1960 (assumed to be average for year) by Takasaki et al (1969)

Given that the source and quality of data, with respect to groundwater withdrawal from the Haʻikū Tunnel, in USGS Water-Supply Paper 1894 (Takasaki et al, 1969) has not been verified, other sources were evaluated during the course of preparing this report for HBWS. Hirashima indicates that between April 1941 and December 1958 that a total of 13,576 million gallons were withdrawn from the Haʻikū Tunnel (Hirashima, 1963). That volume results in an average withdrawal rate of approximately 2.09 MGD between 1941 and 1958. This value is similar, within ~10%, to the average withdrawal rate of 1.88 MGD back calculated for the time period between 1947 and 1957 presented above. Hirashima also indicates that the recharge rate of 2 MGD associated with the Haʻikū Tunnel was calculated over a 6-year period between 1953 and 1958 where apparently it was determined there was little to no change in storage. This tunnel withdrawal rate is corroborated by the data presented in in USGS Water-Supply Paper 1894 (Takasaki et al, 1969) which indicated an average tunnel withdrawal rate of 1.98 MGD between 1953 and 1957. Hirashima does not directly state that storage was depleted during that time period but states that there was no change in storage, meaning the yield (tunnel withdrawal rate) was equal to the recharge rate during that time period.

When comparing the groundwater withdrawal rates from the Haʻikū Tunnel to the stream flows it is seen that post 1980 water withdrawal rates from the tunnel were generally less than 1.3 MGD (with an average less than 0.7 MGD), whereas differences in the flow duration curves up through the 90th percentile were small. It is also noteworthy that water withdrawal from the Haʻikū Tunnel was not performed between February 2010 and February 2014, between December 2015 and April 2017, and also between October 2021 and April 2022 and that the flow duration curves developed for the He'eia Stream were very similar to adjacent years where water withdrawal from the tunnel was performed. With respect to that, a closer look at the He'eia Stream flow duration curves in conjunction with the rain gauge data it is seen that the curves that fall lower on the plot were also years that generally had less total rainfall.

In 1962 and 1963, two papers by Hirashima were published indicating that the construction of the Haʻikū Tunnel affected stream flow of the Kahalu'u Stream during and after its construction. Additionally, he states "the flows in the He'eia, Kahalu'u, and Ioleka'a Streams as well as the Haʻikū and Kahalu'u Tunnels are derived from and sustained by interconnected groundwater reservoirs. Hirashima's analysis presented in these papers provides significant evidence that interconnectivity of the reservoirs exists by comparing the total yield across the three valleys as well as comparison of flows in the He'eia, Kahalu'u, and Ioleka'a Streams to other streams along the windward side of the Ko'olau Range. Refer to Section 2.6 of this report for additional discussion on interconnectivity to the streams and groundwater withdrawal operations within nearby valleys.

2.4 Tunnel Storage Recession Constant

Relationships of tunnel discharge to available storage have been developed for the major groundwater supply tunnels along the Ko'olau Range (Takasaki, 1969). The relationship is as follows:

$$Q_t = Q_0 e^{bt}$$

where:

$$Q_t = Higher\ Discharge\ at\ the\ end\ of\ time, in\ mgd$$
$$Q_0 = Lower\ Discharge\ at\ the\ begining\ of\ time, in\ mgd$$
$$t = time, in\ days$$
$$S = Storage\ at\ time\ t, in\ millions\ of\ gallons$$
$$b = accretion\ constant\ (recession\ constant)$$

When simplified, assuming storage, S, is zero at initial time, the equation becomes:

$$Q_t = bS + Q_0$$

For the Ha'ikū Tunnel the intercept was taken as approximately 2 MGD, which was the average recharge rate for the tunnel between 1953 and 1958 when there was little to no change in storage (Hirashima, 1963). A recession constant of 0.0036 was determined by Takasaki for this tunnel (Takasaki, 1969). Figure 23 below illustrates the storage discharge curve developed by Takasaki (1969) for the Ha'ikū Tunnel and the Waihee Tunnel. Note that the ~2,200 million gallons of maximum storage shown is the sum of the ~1,400 million gallons of storage previously reported (Hirashima, 1963) plus volume associated with the base flow (recharge rate) over the roughly 400-day drainage period if allowed to free flow.

Bowles (1969) questioned the validity of the recession constant determined by Takasaki (1969). He raises those questions by relating his observations of tunnel pressure and withdrawal rate during his study to the values used in the development of the recession curve by Takasaki. Bowles observed a withdrawal rate of 2.4 MGD at a pressure of 23 psi, whereas Takasaki used a maximum withdrawal rate of about 11.6 MGD at 90 psi, at a time of full storage, and a minimum withdrawal rate of 2 MGD at 0 psi, after storage was depleted. After performing a simple linear relationship, it is shown that observations by Bowles do not align with the values used by Takasaki. However, with respect to the pressure measurements Bowles also states:

> *"…..suggesting that the use of discharge line pressure is not a sound measure of aquifer pressure and is adversely influenced by drawdown effects of the tunnel. It is unlikely that the remaining storage was ever useable, however it can be recovered by decreasing the drawdown effects in the tunnel either by extending the tunnel or by drilling a series of horizontal holes at or near the heading."*

Bowles statements appear to be sound. There are many contributing factors that can affect the relationship between the tunnel pressure and withdrawal rates, such as rock mass permeability, the geometry of the reservoir, and effects from nearby groundwater withdrawal operations. Therefore, tunnel pressure and withdrawal rate relationships are likely not linear.

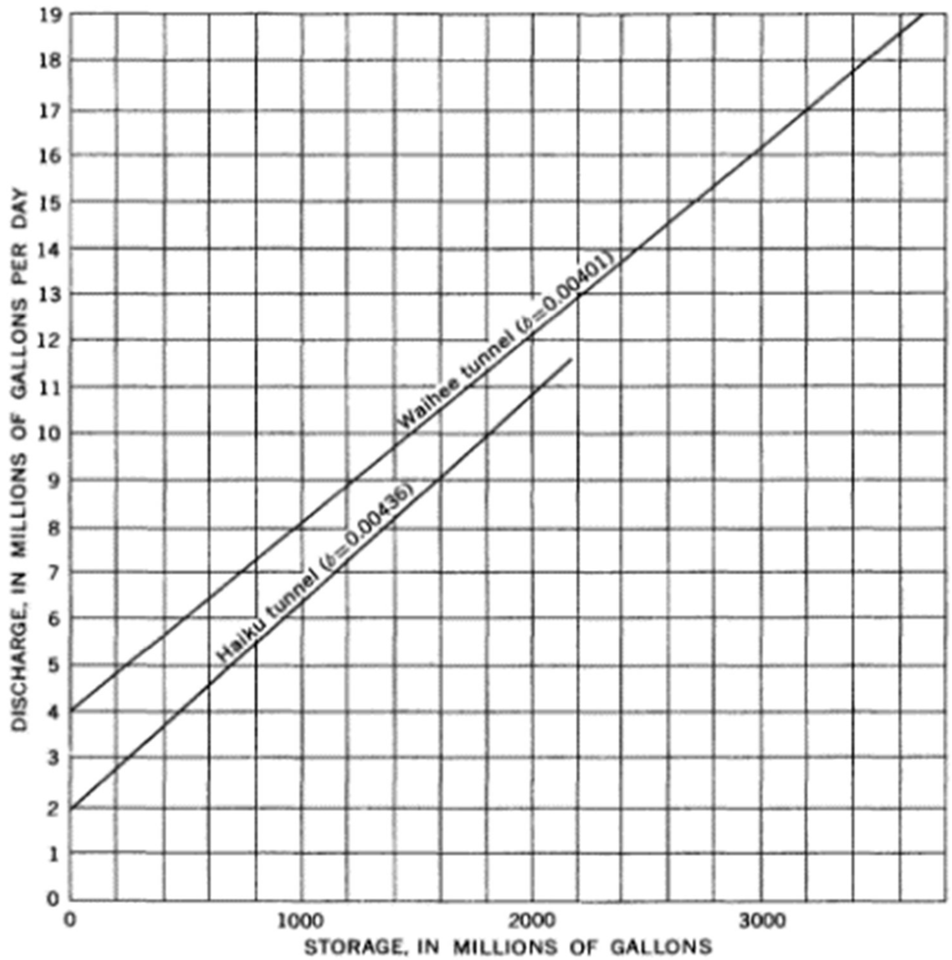
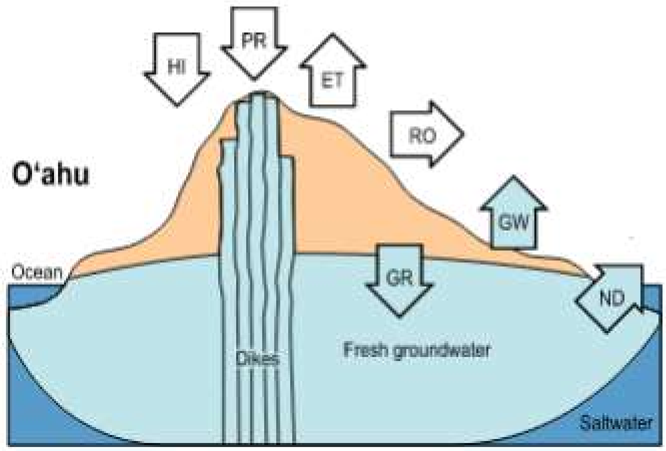


Figure 23: Storage-discharge curves for Waihee and Ha'ikū Tunnels (Takasaki, 1969)

Furthermore, after review of the available data and historic information it appears that during the time that the Ha'ikū Tunnel recharge of 2MGD was determined, the Kahalu'u Tunnel had been constructed and was in operation and construction of the Waihee Tunnel system was ongoing. Historical literature, such by Hirashima (1962 and 1963) and Izuka (1993) provide strong evidence that the dike compartment(s) that supply groundwater to the Ha'ikū Tunnel are also connected to nearby streams and are supplied recharge by ground surface in nearby valleys. Therefore, it is plausible that the storage capacity and recession constant developed for the Ha'ikū Tunnel is not correct and that the values presented in the storage-discharge curve by Takasaki (1969) were influenced by operations in nearby valleys further supporting Bowles (1969) statements regarding its validity.

2.5 Water Budget Studies

The purpose of this section is to present previous water budget studies, assess and understand how much of the groundwater withdrawal from the Ha'ikū Tunnel may be coming from water recharge associated with other nearby drainage basins. A water budget study is essentially an accounting of inflows and outflows to a groundwater system, which is an industry standard, as described by Izuka (2018). Inflow components may include precipitation (PR), including rain and fog, and Human Input (HI), which consists of irrigation, leaks from water supply systems, sewers, and septic systems. Outflow components may include Evapotranspiration (ET), Runoff (RO), Groundwater Recharge (GR), Groundwater Withdrawal (GW), and Natural Discharge (ND), which is discharge from springs, stream base flow, and submarine discharge. An illustration is presented in Figure 24 below.



PR - Precipitation, including rain and fog
HI - Input from Human activities, including irrigation and leaks from water-supply, septic, and sewer systems
ET - Evapotranspiration
RO - Runoff, including runoff from natural surfaces as well as runoff from paved surfaces flowing into storm drains
GR - Groundwater recharge
ND - Natural Discharge, such as spring flow, stream base flow, and submarine groundwater discharge
GW - Groundwater Withdrawal

Figure 24: Illustration of water budget input and output (modified from Izuka, 2018)

As it relates to the use of water budgets to discuss groundwater recharge, two papers that provide important information with respect to the Ha'ikū Valley and Ha'ikū Tunnel will be discussed. Those two papers are USGS Water-Supply Paper 1999-M (Izuka et al, 1993) and USGS Scientific Investigations Report 2015-5010 (Engott et al, 21017). Though previous water budgets performed by others have been found, those water budgets do not include evapotranspiration and other important components. Therefore, they have been considered to be superseded and are not discussed the context of groundwater recharge.

In USGS Water-Supply Paper 1999-M (Izuka et al, 1993) the term water-balance is used rather than water budget. The water-balance presents the average rainfall, calculated direct runoff, actual evapotranspiration, and recharge. Note that total rainfall is based on maps generated from 13 base stations where rainfall data is complete over the 67-year time period and is not necessarily rainfall data directly measured within the Ha'ikū Valley. For this study, the runoff was calculated by calculating the base flow and subtracting that from the readings at USGS 16275000. Base flow was taken as the stream flow at which was exceeded 90% of the time, Q_{90}. Table 7 presents the monthly water balance reported in that paper. Note that recharge would represent the available water for base stream flow, tunnel and well withdrawal, recharge of storage, and water available to move across dike compartments. As seen, the water budget indicates that 1201 MG is available for recharge each year, which is equivalent to about 3.3 MGD.

Table 7: Monthly water balance, for drainage basin gaged at USGS 16275000

Month	Rainfall	Direct Runoff	Actual Evapotranspiration	Recharge
January	185.41	34.21	16.57	134.93
February	136.09	23.95	17.18	95.51
March	184.93	31.29	21.7	136.37
April	154.53	36.92	20.05	95.77
May	128.69	13.87	21.94	94.73
June	87.39	7.51	22.42	57.88
July	115.31	16.63	23.23	76.31
August	136.87	12.48	22.26	101.08
September	118.13	15.06	23.1	80.79
October	138.5	21.39	20.4	93.98
November	158.22	27.55	16.16	110.21
December	182.99	42.43	16.16	124.28
Total	1727.06	283.29	241.17	1201.84

*All values in millions of gallons

Izuka et al (1993) further explain that the recharge area for the tunnel was limited to about 10% of the Ha'ikū Valley plan area, as shown in Figure 25, as it was assumed that a dike was located at STA. 11+80 creating a dike compartment at the end of the tunnel from which the water is drawn. Given this reduced area it is suggested that on a yearly basis approximately 146 MG or 0.4 MGD, of recharge for the Ha'ikū Tunnel comes from rainfall within the Ha'ikū Valley and additional groundwater withdrawal originates from recharge outside the Ha'ikū Valley and/or from storage. This conclusion is in line with those of Hirashima (1963) in that connectivity to dike compartments in other valleys exist. The water budget for this area is provided in Table 8 below.

As discussed in the Sections 2.3 and 2.4 above, Hirashima (1969) indicated that about 2 MGD recharge rate for the Ha'ikū Tunnel existed between 1953 and 1958, which was measured at a time of discharge where storage had little to no change. If the water budget analysis by Izuka et al (1993), that approximated only 0.4 MGD of tunnel recharge can come from within the Ha'ikū Valley, and that the 2 MGD total tunnel recharge rate determined by Hirashima (1969) is reasonably accurate then a significant portion, about 75%, of the recharge for the tunnel was coming from outside the Ha'ikū Valley. As part of the water budget analysis by Izuka et al (1993) 65% of the discharge was estimated to come from outside the Ha'ikū Valley.

However, based on as-built information, the Ha'ikū Tunnel yielded about 1.5 MGD between station 6+00 and 8+00, and another approximately 3MGD between STA 9+00 and 11+80 prior to reaching the heavy flows encountered within the last 50-feet of tunnel. Therefore, the assumed recharge area shown in Figure 25 below may not represent the full extent of the actual dike compartments supplying water to the Ha'ikū Tunnel.

Table 8: Average Monthly water balance, for the recharge area of the dike within the drainage basin gaged at USGS 16275000 (Izuka et al, 1993)

Month	Rainfall	Direct Runoff	Actual Evapotranspiration	Recharge
January	18.46	3.43	0.10	14.95
February	14.23	2.37	0.11	11.68
March	18.46	3.12	0.14	15.24
April	15.16	3.67	0.13	11.31
May	12.90	1.37	0.14	11.38
June	9.02	0.14	0.75	8.11
July	11.75	1.65	0.15	9.95
August	15.09	1.24	0.14	13.66
September	11.75	1.50	0.14	10.09
October	14.73	2.13	0.13	12.42
November	16.31	2.74	0.10	13.42
December	18.46	4.24	0.10	14.13
Total	176.32	27.60	2.13	146.34

*All values in millions of gallons

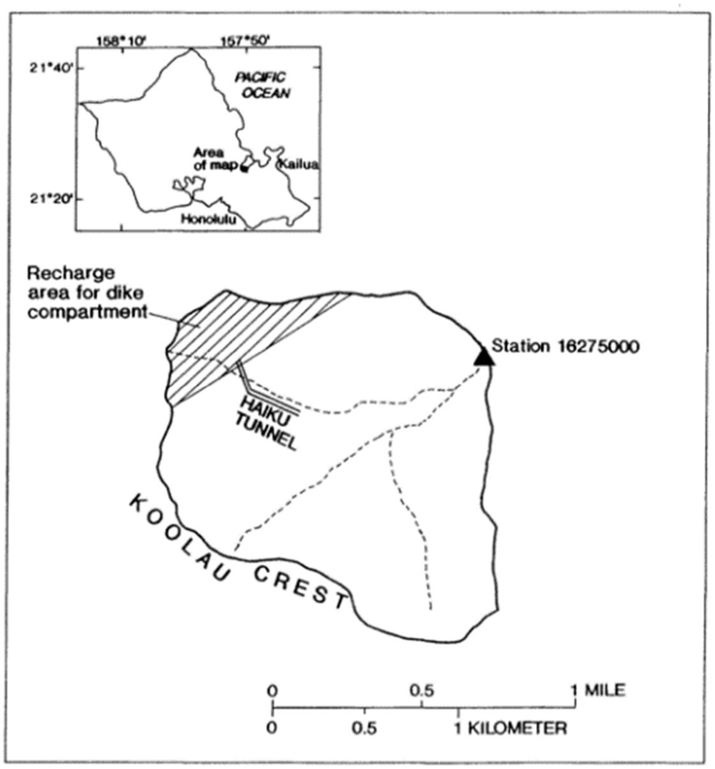


Figure 25: Partial recharge area, in Ha'ikū Valley, for dike compartment from which the Ha'ikū Water Tunnel draws its water (Izuka et al, 1993).

As noted in the beginning of this section, the other report of interest is USGS Scientific Investigation Report 2015-5010 which has a stated purpose "to quantify the spatial distribution of mean annual groundwater recharge for the Island of O'ahu." That report provides all components of the water budget model including the estimated recharge in GIS format for the average and drought conditions. For this study prepared for the HBWS, we are only interested in the mean estimated recharge in the Ha'ikū Valley. The three ground surface areas where evaluated are as follows:

1. Ha'ikū Valley Drainage Basin Gaged at Station 16275000 (refer to Figure 26)
2. Ha'ikū Valley Drainage Basin bound by dike with strike orientation of N26°E crossing Ha'ikū Tunnel at STA. 6+00 (refer to Figure 27)
3. Ha'ikū Valley Drainage Basin bound by dike with strike orientation of N27°W crossing Ha'ikū Tunnel at STA. 6+00 (refer to Figure 28)

The areas are shown in the Figure 26 through Figure 28. These plots show pixilated color zones based on estimated recharge from the water-budget model developed by the USGS (Engott, 2017). Large scale drawings are provided in Appendix D of this report. The dike orientations and locations selected are intended to provide an approximated upper bound surface area to calculate available recharge of the dike compartments which supply the Ha'ikū Tunnel within the Ha'ikū Valley to better assess interconnectivity across the Ko'olau Range. As previously mentioned, it is believed that the recharge area shown in Figure 25 is likely much smaller than actuality, based on review of the historical information. Table 9 presents the recharge in MGD for each of the three recharge areas selected.

The selection of the dike with a strike orientation of N27°W is similar to the orientations shown in the "Geologic and Topographical Map of the Island of O'ahu, Hawaii" that includes dike locations and orientations mapped by H.T. Stearns (1938). Figure 29 presents a screen shot of that map. The dikes observed and drawn by Stearns are circled for convenience. The dikes circled in red have strike orientations ranging from N26W to N58W. The Ha'ikū Tunnel is located in the northwest portion of the valley but is not shown as was not constructed until after the map was developed.

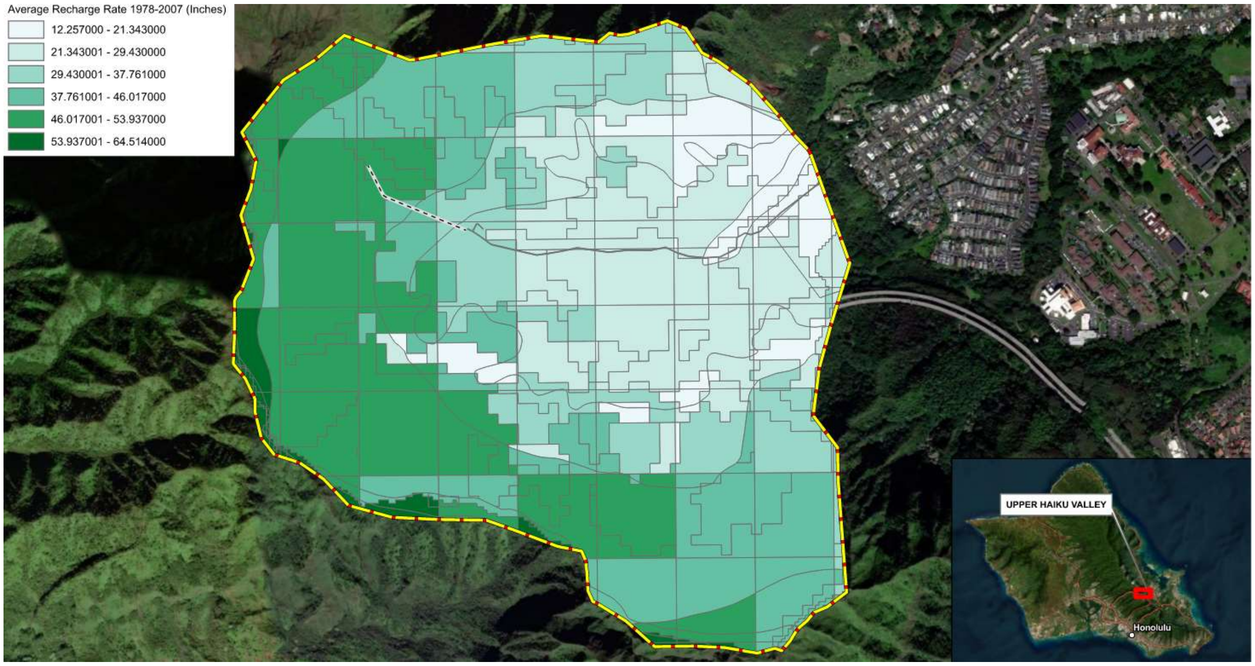


Figure 26: Estimated recharge for Ha'ikū Valley drainage basin gaged at USGS Stream Gauge 16275000

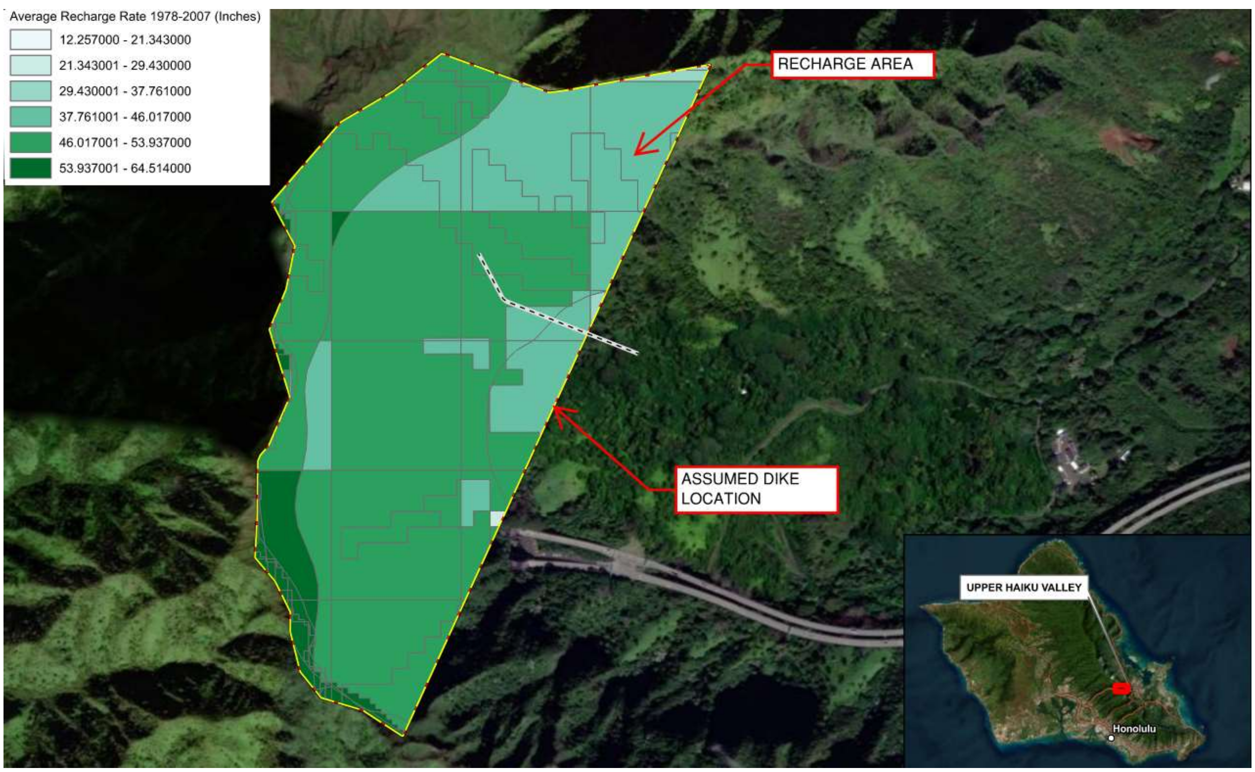


Figure 27: Estimated recharge for Ha'ikū Valley drainage basin bound by dike w/ strike orientation of N26°E crossing Ha'ikū Tunnel at STA. 6+00

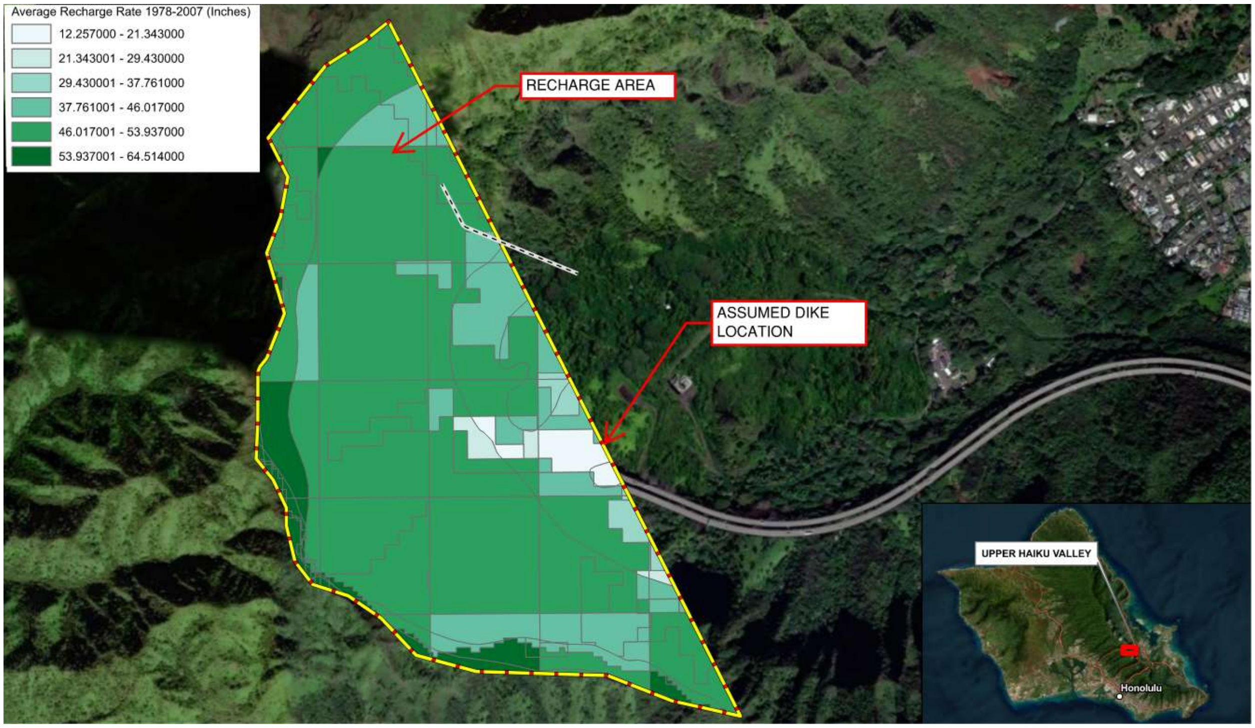


Figure 28: Estimated recharge for Ha'ikū Valley drainage basin bound by dike w/ strike orientation of N27°W crossing Ha'ikū Tunnel at STA. 6+00

Table 9: Summary of recharge estimates for different recharge areas in the Ha'ikū Valley

Recharge Area	Description	Estimated Recharge (MGD)
1	Drainage Basin Gaged at Station 16275000	1.83
2	Drainage Basin bound by dike w/ strike orientation of N26°E crossing Ha'ikū Tunnel at STA. 6+00	0.57
3	Ha'ikū Valley Drainage Basin bound by dike w/ strike orientation of N27°W crossing Ha'ikū Tunnel at STA. 6+00	0.71

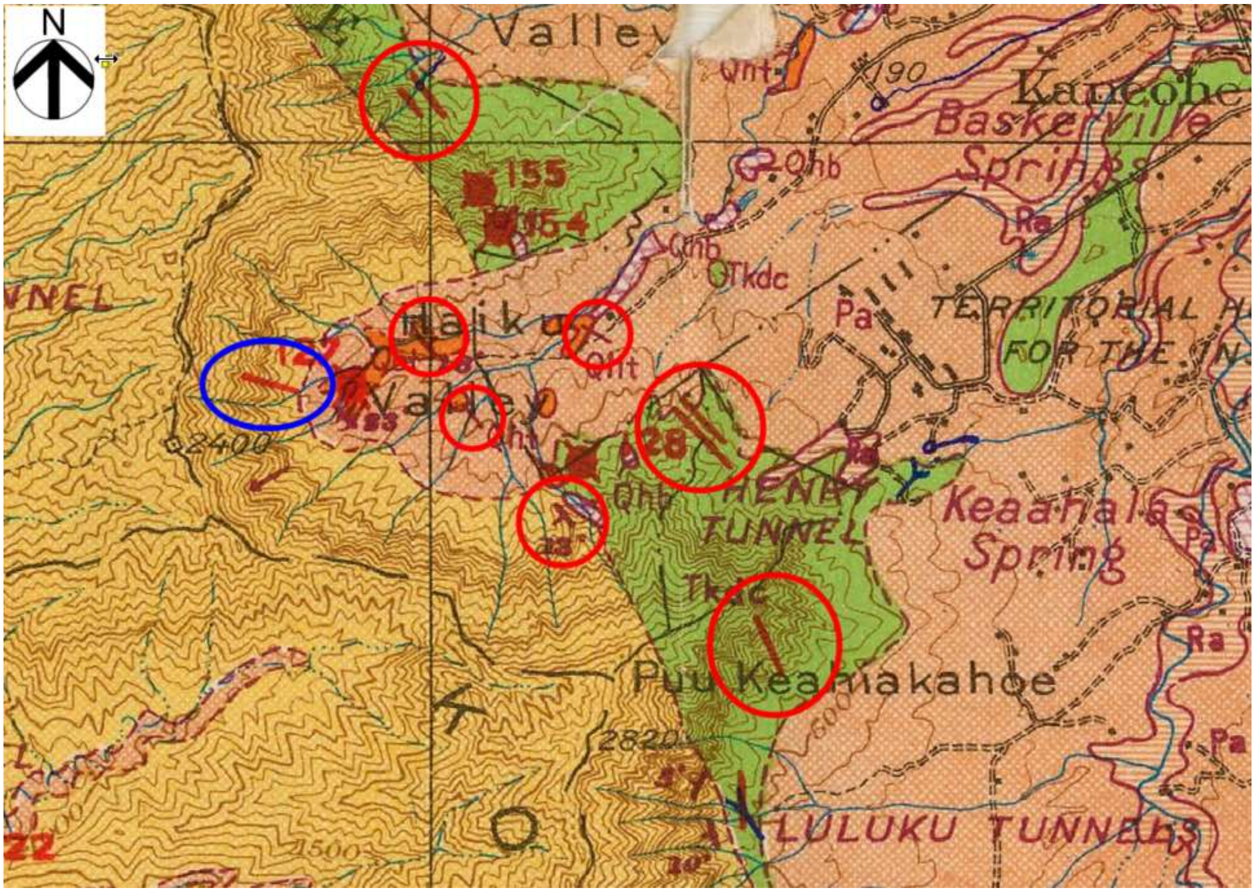


Figure 29: Geologic and topographic map of O'ahu (Stearns, 1938)

As seen in Table 9, the amount of recharge for the dike compartments feeding the Ha'ikū Tunnel that is supplied from within the Ha'ikū Valley is about 0.6 to 0.7 MGD, which should be considered an upper bound. Therefore, if the Ha'ikū Tunnel does have a recharge rate of 2 MGD then a significant portion, 60% to 70%, of the recharge comes from nearby valleys.

Figure 30 below illustrates the steady state and transient states of aquifers. As seen during transient state, the aquifer is either draining or filling due to differences between inflow and outflow. Given the hydrogeologic characteristics of the Ko'olau Range and due to the presence of the dikes, it is our opinion that predevelopment stream flows will never be fully realized during groundwater withdrawal activities. During predevelopment times dike compartments were filled and recharge was generally equal to the natural discharge. As soon as groundwater withdrawal is implemented a new discharge is introduced that takes available water away from that which would have otherwise been part of the natural discharge, thus reducing stream base flow.

Therefore, given that the dike compartments are connected to or extend to nearby valleys, evaluating recharge over greater extents of the Ko'olau Range where groundwater withdrawal operations exist could be performed. This study could assist in determining if the groundwater withdrawal from the Ko'olau Range is in, or close to, a steady state condition or if the compartments are generally in a transition heading towards depletion or filling. The recharge analysis must appropriately consider the effects of dike compartment location variability and the groundwater withdrawal locations.

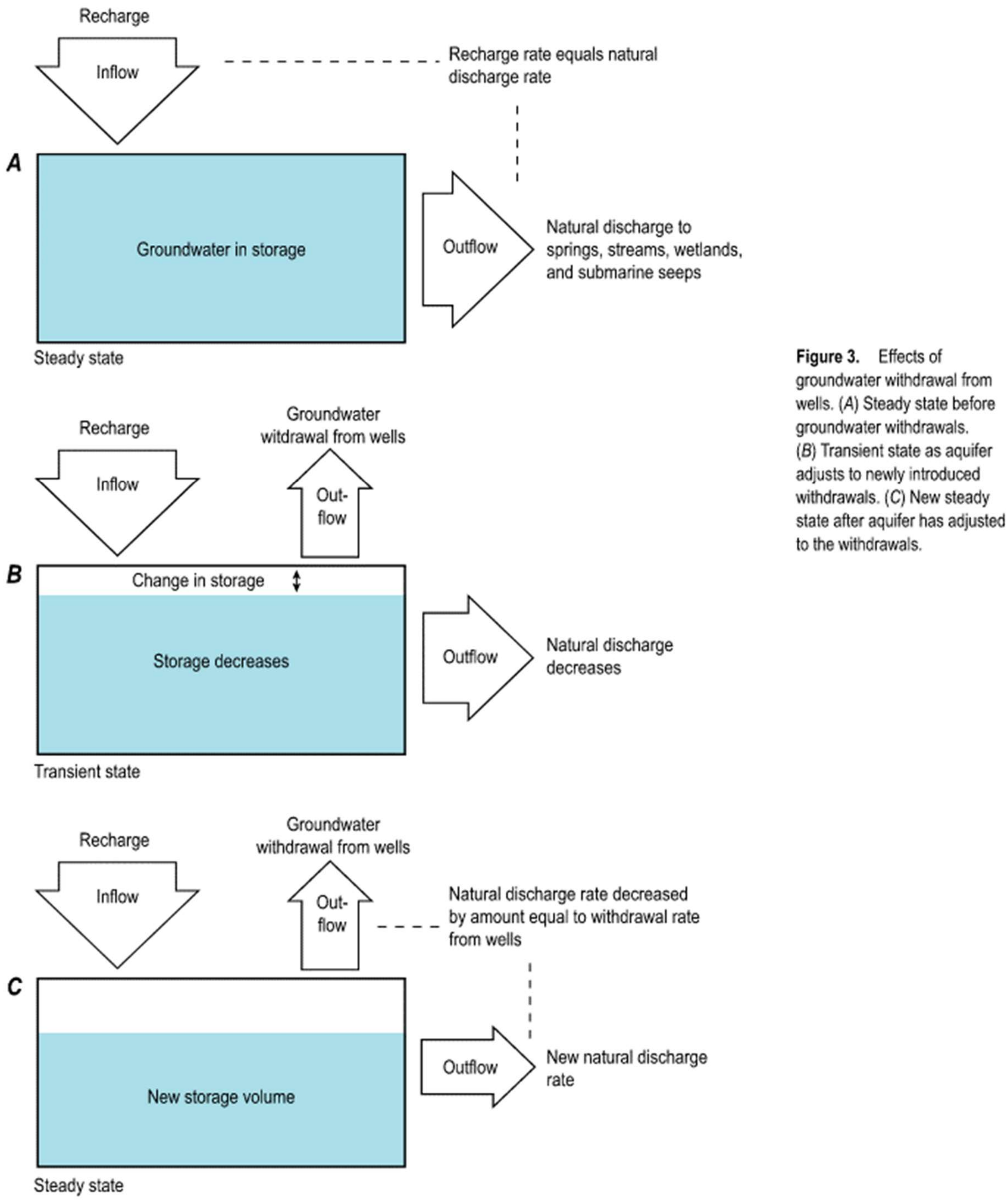


Figure 30: Effects of groundwater withdrawal from wells (Izuka et al, 2018)

2.6 Interconnectivity to the Kahalu'u and Ioleka'a Valleys

The Kahalu'u and Ioleka'a Valleys are located to the North of the Ha'ikū Valley as shown in Figure 31 below. The Kahalu'u Tunnel located in the Kahalu'u Valley was excavated in 1946. The tunnel has a length of about 383-feet and was constructed at an elevation of 585-feet.

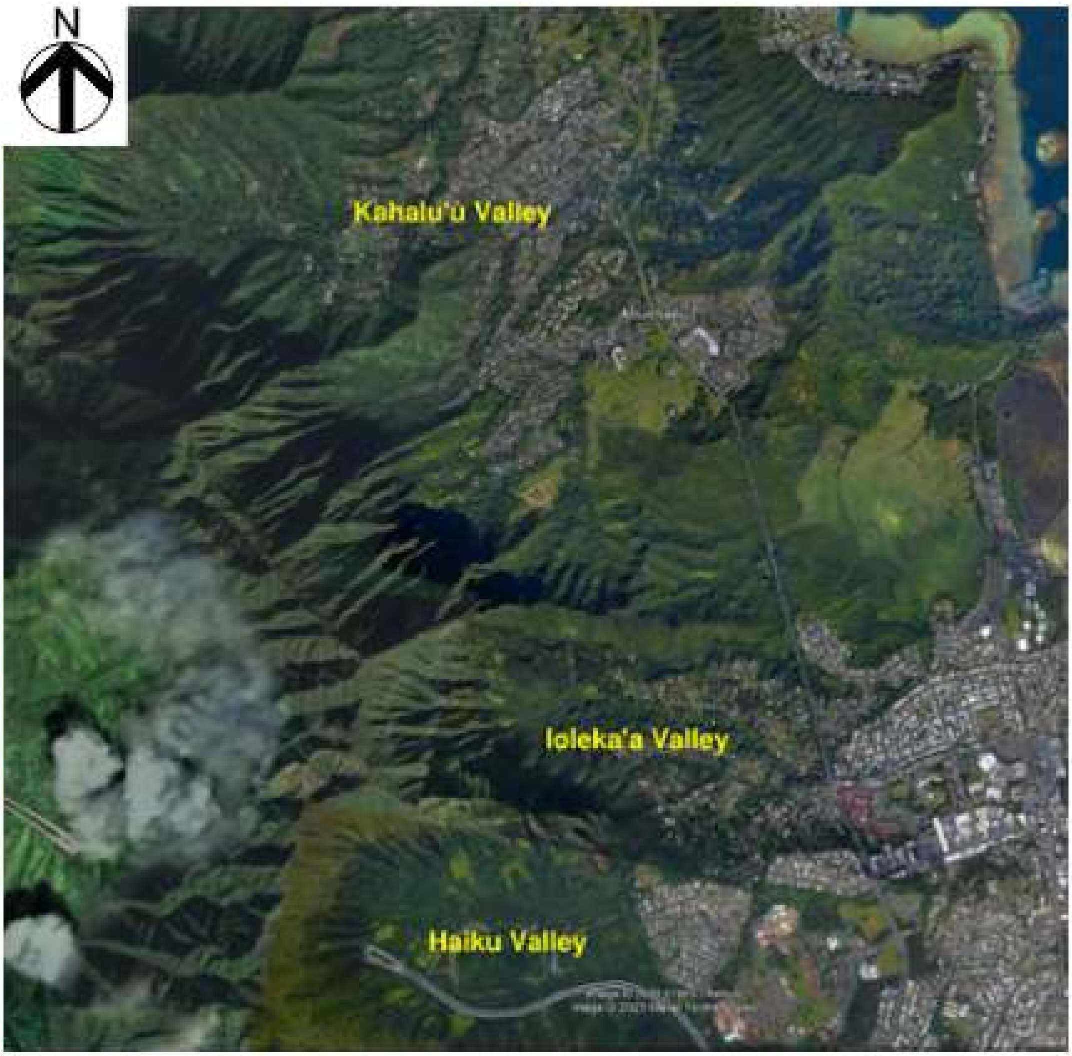


Figure 31: Aerial photo showing location of the Ha'ikū, Kahalu'u, and Ioleka'a Valleys (Google Earth Image, 2023)

To assess the effect of groundwater withdrawal from the Ha'ikū Tunnel on groundwater withdrawal operations and stream flows within the Kahalu'u and Ioleka'a Valley available stream flow data and groundwater withdrawal rates were evaluated. Stream flow data is available from the USGS website for stream gauge 16283200 at the bottom of the Kahalu'u Valley since October 1983, whereas, flow data from the Ioleka'a stream is only available since August 2021 at USGS stream gauge 16278500.

Available groundwater withdrawal rates from the Kahalu'u Tunnel date back to 1959, whereas withdrawal rates from the Kahalu'u well date back to December 1990 and those for the Ioleka'a well date back to May 1985. For all three groundwater withdrawal locations data has been provided through December 1, 2021 by HBWS.

Given the limited available Ioleka'a Stream flow data, the effect of groundwater withdrawal on Ioleka'a Stream flow cannot be assessed at this time. Additionally, based on the relatively low pumping rates for the Ioleka'a well, which never exceeded 0.35 mgd and averaged 0.07 mgd over the 38-year reporting period, the overall effect from that well on the stream flows in the region is likely minimal compared to the Ha'ikū and Kahalu'u Tunnels and potentially the Kahalu'u well.

Figure 32 below presents a plot of available He'eia and Kahalu'u Stream flow measurements and reported withdrawal rates for the Ha'ikū and Kahalu'u Tunnels. As seen in that plot groundwater withdrawal rates from the Kahalu'u Tunnel began to increase in the mid-1990s around the same time and at a similar magnitude to the reduction in withdrawal rates from the Ha'ikū Tunnel. Figure 33 presents a plot of the combined withdrawal rates from the Ha'ikū and Kahalu'u Tunnels since 1959. As seen, the combined withdrawal rate has been fairly level with an average of about 2.4 MGD since 1990. The existence of hydraulic connectivity between the two valleys could explain why measured tunnel pressure in the Ha'ikū Tunnel has not increased over the past two years in which monitoring has been performed as shown in Figure 17.

Data has recently been provided for the Luluku Tunnel and Well operated by HWBS. Since 1990 yearly average groundwater withdrawal rates from the Luluku Tunnel have been less than 0.41 MGD with a mean less than 0.2 MGD. Therefore, given the significantly lower historical groundwater withdrawal rates when compared to Ha'ikū and Kahalu'u Tunnels, conclusions with respect to interconnectivity cannot be drawn at this time without further analysis and data collection.

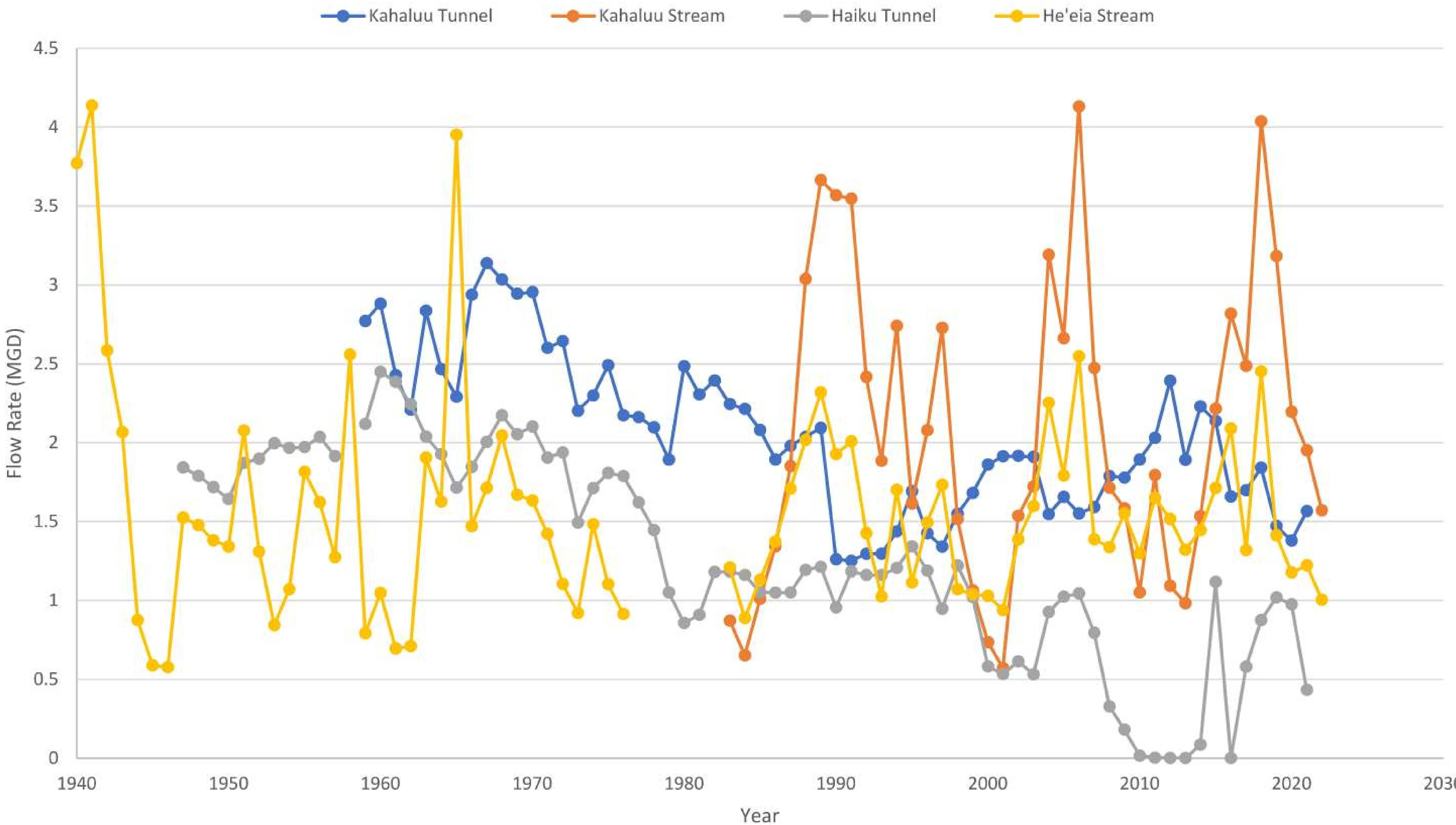


Figure 32: Plot illustrating He'eia and Kahalu'u Stream flow and Ha'ikū and Kahalu'u Tunnel withdrawal rates

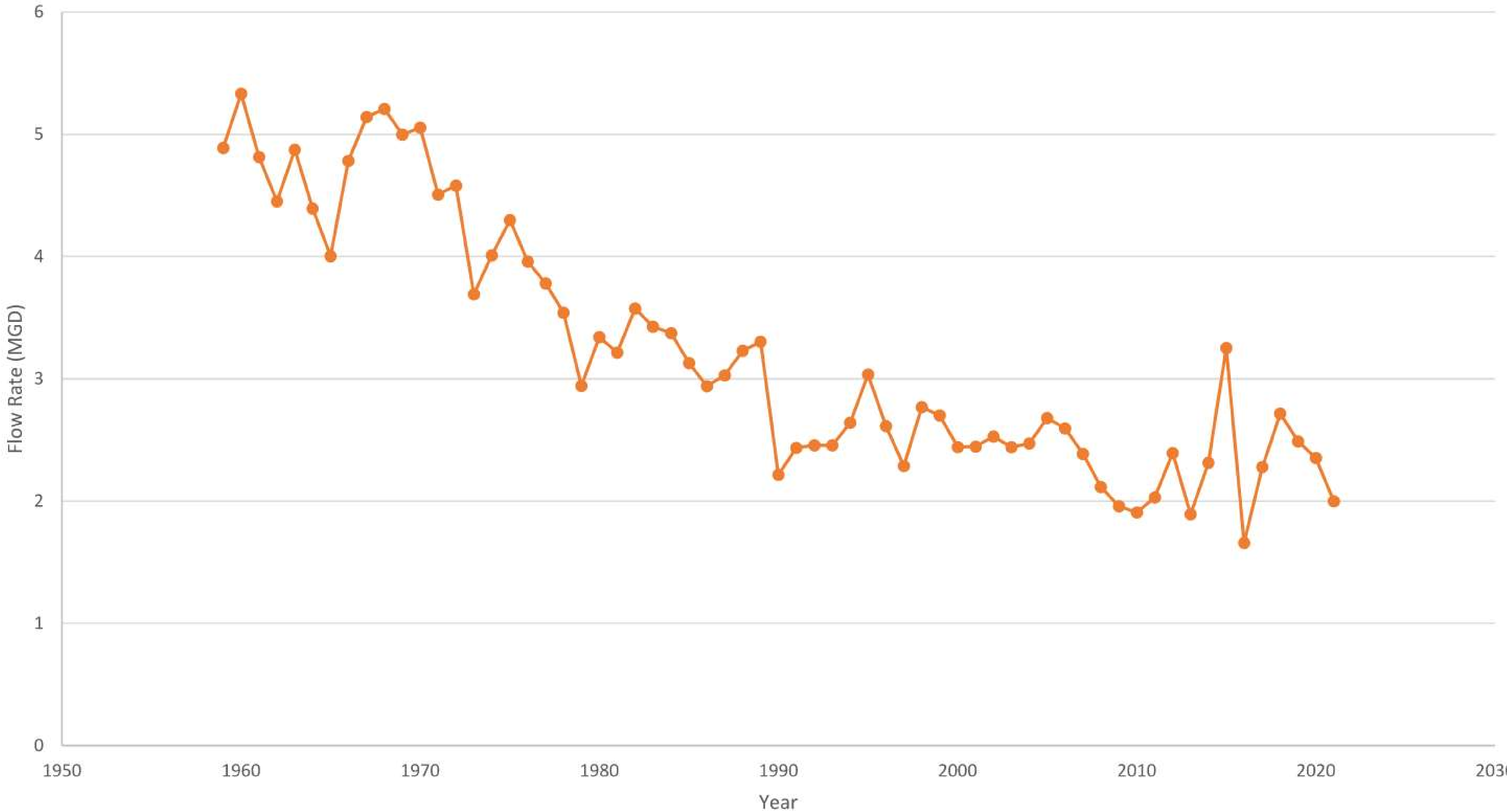


Figure 33: Plot illustrating combined Ha'ikū and Kahalu'u Tunnel withdrawal rates

2.7 Summary

- Water source compartments are developed by vertical dikes extending up through the basalt rock mass. Water is stored within the porous rock mass and the tunnel functions as a horizontal well puncturing through the dikes into each of the storage compartments. During construction of the Haʻikū Tunnel excavation of the tunnel through multiple dikes occurred.

- As-built records and the inspection by Bowles in 1969, appear to indicate that 3 dike compartments are connected via the tunnel and control of groundwater leakage from one compartment to another does not exist.

- Available information appears to indicate that a dike is located at Bulkhead No. 3 and that Bulkhead No. 3 has an open 9-foot section of 36-inch diameter pipe passing through it. If this is true, then the two dike compartments up-station are constantly supplying water to the compartment between Bulkhead No. 3 and Bulkhead No. 2.

- Based on the elevations of the reported activated springs supplying water to the He'eia Stream, it is likely that those springs are fed by the compartments down station from Bulkhead No. 3.

- Pressure monitoring data, as provided by HBWS, reveal that during the tunnel shut down between October 2021 through April 2022 the tunnel reached an internal pressure of about 47 psi. This pressure is lower compared to the 90 psi shut-in pressure reported in December 1940. However, the effects of potentially hydraulically connected tunnels and wells that were installed in Ha'ikū Valley and nearby valleys post-1940, as well as the extended period of drought during 2021 and 2022, likely affected the maximum pressure recorded during the October 2021 to April 2022 Ha'ikū Tunnel shutdown. Since April 2022, the withdrawal rate has been steady at 0.35 MGD and monitoring at the portal has indicated a relatively steady groundwater pressure of 43 psi.

- Based on the available information it appears that there has been a reduction in the He'eia Stream flow since the withdrawal of water from the Haʻikū Tunnel began in December 1940. Significantly lower He'eia Stream flows were observed shortly after construction of the Haʻikū Tunnel until about 1963, whereas since 1964 stream flows have been relatively steady with a Q_{90} generally between 1.0 MGD and 2.0 MGD. However, this is based on comparisons to a limited available data set prior to the construction of the Haʻikū Tunnel.

- As part of USGS Water-Supply Paper 1894 (Takasaki et al, 1969), the long-term Q_{90} of the stream was estimated to be 1.2 MGD for the base period between 1927 and 1960 based on correlations with the East Branch Manoa Stream given that limited stream data prior to construction of the Haʻikū Tunnel. This estimate is similar to the Q_{90} values calculated since 1964.

- Estimates by Hirashima (1963) suggest that a recharge rate of 2 MGD exists based on withdrawal rates between 1953 and 1958 and if withdrawal from the Haʻikū Tunnel were to cease it would take approximately 2 years to fully recharge the dike compartments. However, as indicated by Izuka et. al (1993) some of that recharge may be supplied from other drainage basins, such as the Kahalu'u, and Ioleka'a Valleys due to extension of the dike compartment to those valleys or interconnectivity between dike compartments along the Ko'olau Range.

- During tunnel construction and initial shut-in a reportedly 90-psi internal tunnel pressure was reached in 1940. However, given the interconnectivity between the dike compartment that supplies the Haʻikū Tunnel and those that supply streams and groundwater withdrawal operations in the Kahalu'u, and Ioleka'a Valleys the 90 psi internal pressure may never be realized with today's conditions.

- Between August 2021 and April 2023 withdrawal rates have been significantly lower than the originally reported 2 MGD recharge rate. Haʻikū Tunnel internal pressure has remained relatively steady at about 43 psi +/- since the water withdrawal from the Haʻikū Tunnel was restarted in April 2022 at approximately 0.3 MGD.

- Estimated recharge rates pertaining solely to the Haʻikū Valley indicate that the dike compartment(s) which supply groundwater to the Haʻikū Tunnel must extend to or are connected to nearby valleys along the Ko'olau Range.

- Measured water withdrawal rates considering only the Haʻikū and Kahalu'u Tunnels shows that as groundwater withdrawal rates were reduced from the Haʻikū Tunnel the groundwater withdrawal from Kahalu'u Tunnel was increased nearly at the same rate. Given the likely connection or continuity of the dike compartments that supply the groundwater to both tunnels, could explain why internal tunnel pressure within Haʻikū Tunnel has not increased as groundwater withdrawal from it has decreased.

3 ALTERNATIVES CONSIDERED

Based on our understanding developed during the course of this study, Brierley has evaluated five alternatives to be considered as described below. Feasibility of alternative construction is presented in Section 4. It is important to note that as previously indicated in studies by Hirashima (1963) and Izuka et al (1993) interconnectivity or extension of the dike compartments to nearby valleys exist. Therefore, if any of the bulkheading alternatives presented below are employed, full potential may never be realized due to water withdrawal operations occurring in the Kahalu'u and Ioleka'a Valleys. Additionally, there is also potential that groundwater loss through the lined section of the Haʻikū Tunnel between STA 8+15 and STA 9+00, loss across the dikes, and/or loss due to the operation of the Ha'ikū well are contributing to the inability to reach full storage within a dike compartment.

The Bowles report also recommended extending the tunnel approximately 100-feet or drilling a series of small diameter holes at the end of the tunnel (STA 12+00) to better connect, hydraulically, the tunnel to the higher permeability clinker encountered in last compartment. As it relates to the first three alternatives presented below, the combination of both bulkhead installation and extending the tunnel or drilling small diameter holes at the end of the tunnel has the potential to increase storage capacity and increase the peak discharge rate of the tunnel.

3.1 Alternative 1: Installation of a Bulkhead at ~STA 11+78 (CWRM)

Similar to the CWRM order, Hirashima's 1971 paper "Tunnels and Dikes of the Ko'olau Range…" also provides a recommendation that states "additional bulkheads are needed, especially one at the site of the 10-foot dike 1,200-feet from the portal," but does not specify any other locations. However, as previously mentioned, the original construction documents and the Bowles report contain contradictory information about the conditions at the end of the tunnel.

If Bowles is correct that a dike does not exist near the end of the tunnel (~STA 12+00), then placement of a bulkhead at this location may not be appropriate. If this clinker zone is present within the same dike compartment that exists beyond STA 9+80 then it is still hydraulically connected to the surrounding less permeable rock within that compartment. The less permeable rock will continue to supply or draw water from the clinker bed regardless of the installation of a new bulkhead. Therefore, the intended result from bulkhead installation will likely never be fully attained.

If a dike does exist immediately before the zone identified by Bowles as clinker, then installation of a bulkhead would theoretically provide a compartment with a greater storage height given that these dikes may extend to a potentially higher elevation.

3.2 Alternative 2: Installation of a Bulkhead at STA 9+80 (Bowles)

The Bowles report recommended that a 4th bulkhead be constructed at STA 9+80. Per his tunnel mapping, a 3.5-feet thick dike was observed at STA 9+80 and no dike is located beyond that station along the tunnel alignment. Given the location of that dike, and assuming that the dikes are generally oriented near-vertical, Bowles anticipated that the dike at STA 9+80 most likely extends to a higher elevation than the down station dikes.

If a bulkhead is constructed at STA 9+80 and piping extended to it, then there is the potential to utilize a dike compartment with greater height to store additional water without continued loss to the down station dike compartments. Currently, as groundwater within dike compartments between STA 9+00 and STA 9+80 and between STA 9+80 and the end of tunnel, enters the tunnel, that groundwater may freely flow into the dike compartment between STA 6+00 and 9+00 which most likely has a lower storage height. This statement assumes that Bulkhead No. 3 is open, and that piping does not extend from Bulkhead No. 2 to Bulkhead No. 3, refer to Section 1 of this report for the discussion regarding Bulkhead No. 3.

Water pressure measurements taken behind the location of Bulkhead No. 2 were at about 47 psi between October 2021 and April 2022 when the tunnel was apparently “shut down” as noted in pressure sensor data provided by HBWS. If those measurements are accurate and the compartment was full it would indicate a maximum storage height at about EL 664-feet +/-. However, given that ground elevation above this compartment is significantly higher than EL 664-feet it is likely that the compartment is not full, and that groundwater is flowing into other dike compartments or that the dike compartments extend into other valleys where other groundwater withdrawal operations are ongoing.

3.3 Alternative 3: Installation of Pipe from Bulkhead No. 2 through No. 3

Currently, there is no evidence that the interior pipe extends from the up-station side of Bulkhead No. 2 to Bulkhead No. 3 as discussed in Section 1 of this report leading to the conclusion that Bulkhead No. 3 is open. The Bowles report shows a 36-inch diameter casing penetrating through Bulkhead No. 3, the pipe reportedly extends 1-foot down station of the bulkhead and approximately 4-feet beyond the bulkhead in the up-station direction. The purpose of this casing appears to be solely to act as a passageway, for water and personnel, through the open bulkhead.

If the existing 12-inch pipe was extended from Bulkhead No. 2 to Bulkhead No. 3, there is potential that the dike compartments intercepted beyond STA 9+00 could fill up to the height of the compartment between Bulkhead No. 3 and STA 9+80, resulting in an increase of storage capacity. This option would not require that new bulkheads be constructed, but only that piping passing through Bulkhead No. 2 is extended to pass through Bulkhead No. 3. However, this assumes that Bulkhead No. 3 has been constructed within the dike observed at or around STA 9+00 and would serve as an effective seal. It would be prudent to perform a physical investigation to determine if a dike exists at this location prior to developing final bid documents for installation of the pipe.

Closing Bulkhead No. 3 and installing a pipe through it may result in a similar outcome as if the bulkhead was installed at STA 9+80. This is due to the fact that the ground surface elevation at each of the encountered dikes is relatively close to one another and therefore storage height potential may be similar. Figure 34 presents a marked up version of the Haʻikū Tunnel profile presented earlier in this report as Figure 15, theorizing that the dike at the location of Bulkhead No. 3 may extend high enough to provide the means for additional storage height. Based on the topography at the location of that dike it is plausible that 90 to 95 psi pressure in the tunnel could be reached if adequate recharge, as compared to the withdrawal rates, is available. However, this theory relies on the dike extending up to high enough elevations which is unknown.

This alternative also has potential to allow groundwater within the dike compartment between Bulkhead No. 2 and Bulkhead No. 3 to fill to its maximum storage height and continue to feed the stream without discharging into the Ha'ikū Tunnel. Furthermore, it should mitigate loss of groundwater stored in compartments located beyond Bulkhead No. 3 into the compartment(s) down station from Bulkhead No. 3 via the Ha'ikū Tunnel.

It appears modification of Bulkhead No 3 to allow extension of the piping from Bulkhead No. 2 to Bulkhead No. 3 will be significantly less invasive on the tunnel and surrounding environment. For this approach, the old piping between the access portal and Bulkhead No 2 would be removed. Bulkhead No. 3 would be modified as required to receive piping and construct a drainpipe, then new piping would be installed between the access portal, through Bulkhead No. 2 and through Bulkhead No. 3. The bulkheads would be sealed around the pipe so that groundwater from behind bulkhead No. 3 cannot pass through and enter the compartment between Bulkheads No. 2 and No. 3 and similarly at Bulkhead No. 2 to prevent leakage at that bulkhead. For this option, groundwater will only be withdrawn from behind bulkhead No. 3, leaving the dike compartment between Bulkheads No.2 and No. 3 potentially untapped to allow natural recharge and discharge, that is unless that compartment extends to or is interconnected to compartments that are tapped by groundwater withdrawal operations in other valleys. That connection or extension will likely not be determinable until this type of operational change is implemented. Alternatively, an additional pipeline could be installed to allow withdrawal of water from either the dike compartment between Bulkhead No. 2 and No. 3 or the dike compartments up station from Bulkhead No. 3.

Other incidental modifications to the bulkheads such as coring holes through Bulkheads No. 1 and No. 2 to allow passing of ventilation lines through them may be required to facilitate the work in accordance with current safety regulations and standards, however, if the work is sequenced correctly the existing penetrations could be used for both ventilation and access but vent lines would likely need to be flexible and easy to disconnect to allow passage.

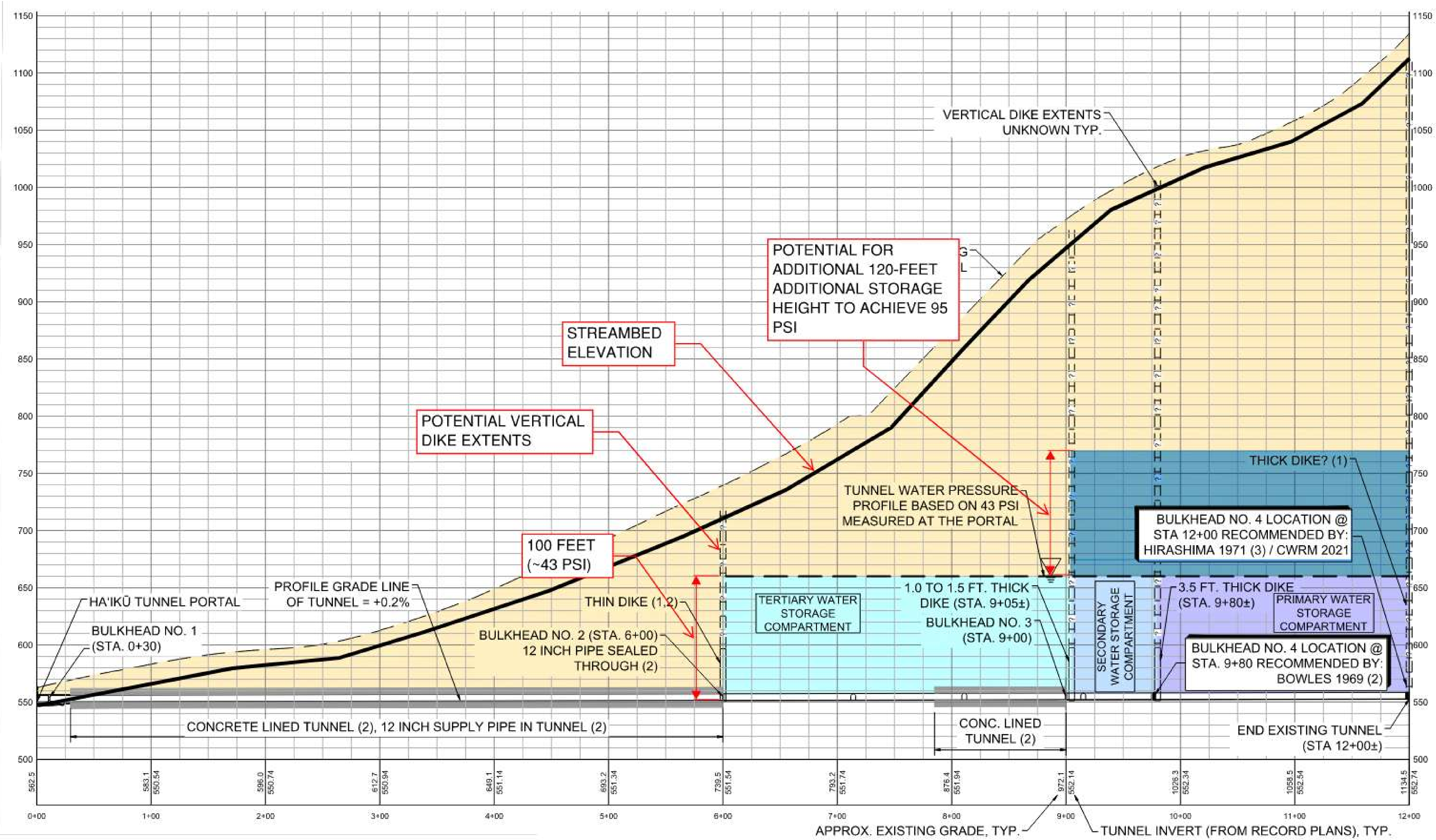


Figure 34: Potential additional storage height gained by closing Bulkhead No. 3

3.4 Alternative 4: New Horizontal Tunnel

Instead of new bulkhead construction or installation of additional piping, the existing tunnel could be abandoned, and an entirely new tunnel driven via trenchless methods. This alternative would require decommissioning of the existing Ha'ikū Tunnel. The work would entail, at minimum, sealing up the connections between the dike compartments to mitigate the existing tunnel effect on the hydrogeological aspects of the Ha'ikū Valley and nearby valleys.

To accomplish this, a new water transmission main sized to transmit up to 2.0 MGD would be installed at an approximate length of 2,200 LF from the existing accessible area near Ha'ikū Well up to the highly permeable clinker bed encountered at the end of the Ha'ikū Tunnel. Trenchless methods such as Horizontal Directional Drilling (HDD) and Microtunneling/Direct Pipe Technology provide options for construction in difficult locations and ground conditions such as would be encountered on this project.

Understanding the complex ground conditions within the area is fundamental to successful project delivery. The basalt and clinker expected to be encountered within the project area will be challenging to excavate. The material itself is expected to have a wide range of Unconfined Compressive Strength (UCS) values, and is known to be highly abrasive, which will create installation challenges for both HDD and tunneling applications.

The existing groundwater conditions are also critical in determining the appropriate manner of construction. The dike compartments will need to be depressurized to mitigate risk of unintended and uncontrolled hydraulic connectivity during the tunneling operations and to ensure adequate grouting after pipe installation to mitigate the potential of enhanced interconnectivity of the compartments due to construction. It would likely be possible to use the Ha'ikū Tunnel to perform this depressurization, as the tunnel would be required to be depressurized to perform the decommissioning work.

To perform the tunneling operations an area of about 15,000-sf would be needed for the equipment and material storage which appears to be achievable in the access road location.

Based on experience, this option is considered to be significantly more costly than the other alternatives presented and is not recommended for further consideration.

3.5 Alternative 5: No Build/Future Build

As described throughout this report, the dike compartment that supplies water to the Ha'ikū Tunnel must be connected to, or extend to, nearby valleys. This is evident when evaluating the recharge associated with the potential footprint of the dike compartments. Additionally, evidence has been put forth by Hirashima (1962 and 1963) that flow in the Kahalu'u Stream reduced by about 25% during the construction of the Ha'ikū Tunnel, when groundwater was allowed to freely flow out. Given this interconnectivity between the valleys further analysis of the global effect of water withdrawal operations along the Ko'olau Range could be performed prior to allocating funds for and performing construction for elements where achievement of the desired result, especially the degree of achievement, is very uncertain.

The uncertainty associated with the effectiveness of a bulkhead is primarily associated with the interconnectivity or extension of the dike compartments to nearby valleys and the numerous active groundwater withdrawal operations. As previously noted, the withdrawal rate from the Ha'ikū Tunnel has been reduced to about 0.3 MGD since August 2021. Pressure data taken from within the discharge pipe at the tunnel portal, which is available dating back to late December 2021, has not indicated increased groundwater pressure since that time. Whereas, evaluation of the spatial recharge estimates would suggest that the 0.3 MGD withdrawal rate is most likely less than the recharge associated with the dike compartments supplying water to the Ha'ikū Tunnel. Additionally, there has been no indication that excess groundwater has leaked out of the tunnel and entered the He'eia Stream. Therefore, the available recharge must be flowing underground to other locations.

Significant evidence has been discussed herein that indicates the dike compartments that supply groundwater to the Ha'ikū Tunnel are connected to or extend to adjacent valleys, most notably the Kahalu'u Valley. Groundwater withdrawal tunnels are located within those valleys as well. Section 2.6 presents data that demonstrates as the groundwater withdrawal rates for the Ha'ikū Tunnel decreased, the withdrawal rates from the Kahalu'u Tunnel increased similarly in magnitude. Therefore, if connection exists the net change in groundwater withdrawal from the dike compartment(s) was insignificant. This is most likely the reason that pressure within the Ha'ikū Tunnel has not increased since late 2021. Subsequently if bulkheading were to be performed it might not affect the quantity of stored groundwater within those dike compartments as it is plausible that the dike located at bulkhead No. 2 extends well above the current top of groundwater elevation.

Significant work by the USGS has been performed to develop an island-wide water-budget model to estimate the mean annual recharge for the island. Brierley understands that this water budget model and recharge estimates are currently being updated. When available, these updated recharge estimates could be part of an effort to further assess storage recharge rates for Ha'ikū Tunnel.

3.6 Summary

Although the concept of bulkhead construction to improve water storage at Sta 11+78, as identified in the CWRM order and suggested by Hirashima (1971) and similarly by Bowles but at Sta 9+80, the effectiveness of such bulkheads or even a new tunnel might not be as expected. Prior studies by Hirashima (1963) and Izuka et al (1993) as mentioned in this report for HBWS surmised that interconnectivity or extension of the dike compartments to nearby valleys exist. Therefore, full storage potential may never be achievable due to water withdrawal operations occurring in the Kahalu'u and Ioleka'a Valleys. Other more local characteristics that need to be assessed include:

- If absence of a dike near the end of the Ha'ikū Tunnel (~STA 12+00) as surmised by Bowles is correct, then placement of a bulkhead at this location would not be appropriate. If the clinker zone identified by Bowles, is present within the same dike compartment that exists beyond STA 9+80 then it is still hydraulically connected to the surrounding less permeable rock within that compartment. The less permeable rock will continue to supply or draw water from the clinker bed regardless of the installation of a new bulkhead. Therefore, the intended result from bulkhead installation will likely never be obtained.

- If a dike does exist at or within the zone identified by Bowles as clinker, then installation of a bulkhead would theoretically provide a compartment with a greater storage height given that these dikes typically extend nearly to the ground surface. However, there is potential for groundwater loss through the lined section of the Ha'ikū Tunnel between STA 8+15 and STA 9+00, loss across the dikes, and/or loss due to the operation of the

Ha'ikū well occurred during that time period preventing the dike compartment from reaching its full potential.

- Currently, there is no conclusive evidence that the interior pipe extends from the up-station side of Bulkhead No. 2 to Bulkhead No. 3. If modifying Bulkhead No. 3 by extending the existing 12-inch pipe, as reported by Bowles, there is potential that the last two or three encountered dike compartments could fill up to the height of the compartment between STA 9+80 and Bulkhead No. 3, resulting in an increase of storage capacity. However, prior to progressing the design or constructability of this alternative, additional investigation would be required to determine if a dike does exist, and that Bulkhead No. 3 was in fact constructed at a dike.

- Construction of a new horizontal tunnel is not a recommended alternative due to the cost.

- Use of a pending updated water budget and recharge model may be beneficial to further assess storage recharge rates.

4 FEASIBILITY OF CONSTRUCTION ALTERNATIVES

This section is focused on implementation of Alternatives 1 through 3 as presented in Section 3.

4.1 Site Access Logistical Considerations

In order to assess the logistical constraints associated with this project Brierley performed a site visit in November 2021. The logistics associated with performing major construction works at the Ha'ikū Tunnel will be extremely difficult. Access to the site is via Ha'ikū Road through several residential neighborhoods on the outskirts of Kaneohe. From there, the roads are relatively narrow and ill-suited for a significant volume of heavy traffic so improvements will be needed to facilitate construction traffic. Figure 35 and Figure 36 are screen shots from Google Earth showing the site and access locations. Access to the Ha'ikū Tunnel portal can only be attained via an approximately 800-feet long hiking trail, as shown in the photograph in Figure 37. Depending on environmental permitting constraints, the trail could be widened to allow smaller vehicular and equipment traffic from the access road to the portal, an elevated accessway could be constructed to mitigate impact to the vegetation, or a combination thereof. If an elevated accessway is required it can be reasonably assumed that equipment across the platform would be limited to relatively light duty type, and because of that, the required manpower, time, and costs would increase accordingly.

Figure 35: Google Earth Image for access to the Ha'ikū Tunnel Portal

Figure 36: Google Earth Image for access to the Ha'ikū Tunnel Portal

Figure 37: Photograph of Hiking Trail to Ha'ikū Tunnel

4.2 Fourth Bulkhead Construction (Alternatives 1 and 2)

Review of the available as-built information reveals that some components within the tunnel will need to be removed to facilitate construction of a fourth bulkhead. A 12-inch diameter pipe extends from the 90-degree bend at the portal through the tunnel to Bulkhead No. 2, as shown in Figure 38 below. To complete this work the 12-inch pipe would need to be removed from the tunnel and significant consideration should be given to replacement of the roughly 80-year old pipe to extend the design life and minimize the potential for later unanticipated tunnel entry.

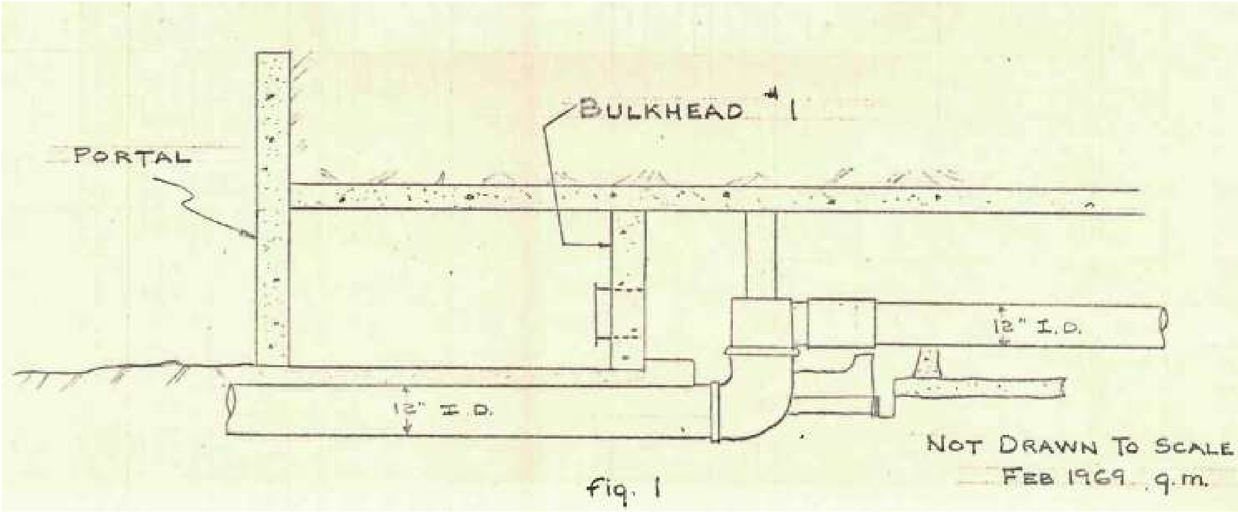


Figure 38: Schematic of Tunnel and Existing Internal Piping at Portal - From Bowles Planning Study

Bulkheads No. 1, No. 2 and No. 3 present significant restrictions associated with personnel access, material transportation, and ventilation during the work. The schematic in Figure 39 and Figure 40 illustrate the geometry of Bulkhead No. 2 and No. 3, respectively. As seen, there is one 36-inch diameter penetration through each bulkhead. Per photographs presented in the Bowles report, Bulkhead No. 1 appears to be similar to the others with the difference being that the location of the penetration is higher in section as shown in Figure 41. It would be very difficult, if not impossible, to maintain adequate ventilation lines and drainage piping through this opening while simultaneously using it as access for personnel and material movement to facilitate the work. Therefore, complete removal of these bulkheads is recommended to be performed to allow the work to be performed more efficiently with fewer safety risks when using conventional construction techniques.

New bulkheads would be constructed at the locations of the existing ones along with construction of the new 4th bulkhead. Installation work would commence at Bulkhead No. 4 then progress down station towards the portal. Piping would then be installed through each bulkhead and sealed to prevent groundwater from flowing between the dike compartments using the tunnel as a conduit. Given that the as-built information (circa 1940) and inspection report by Bowles (1969) suggest that three (3) dike compartments were tapped, multiple pipelines can be installed to provide the operational control to withdrawal groundwater from each individual dike compartment or isolate any compartment at any time. The decision to utilize two or three pipelines depends on determining if the closure of Bulkhead No. 3 is part of the work or leaving it open as it currently is. Each pipeline can be equipped with real-time pressure sensors to monitor the groundwater pressure within each compartment.

The current condition and stability of the tunnel is not known. Therefore, if major work is to be performed beyond Bulkhead No. 2 an inspection by a licensed tunneling Geologist and/or Engineer would be warranted to ensure that entry can be done safely and to determine if and where rock support is required. Given that tunnel entry has not been performed in more than 50 years, since Bowles inspection in 1969, there is potential for destabilization of rock wedges during depressurization. It is recommended that prior to initial person entry utilization of robotic equipment to assess existing tunnel conditions and potential safety hazards is performed. Once that information is gained, decisions can be made on how safety risks could be mitigated.

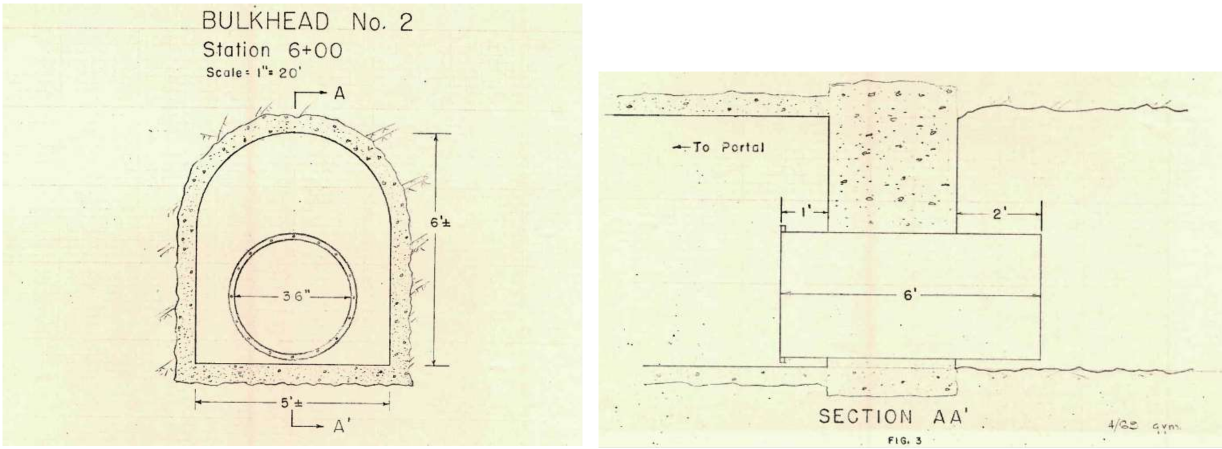


Figure 39: Schematic of Bulkhead No. 2 (STA 6+00) - From Bowles Report

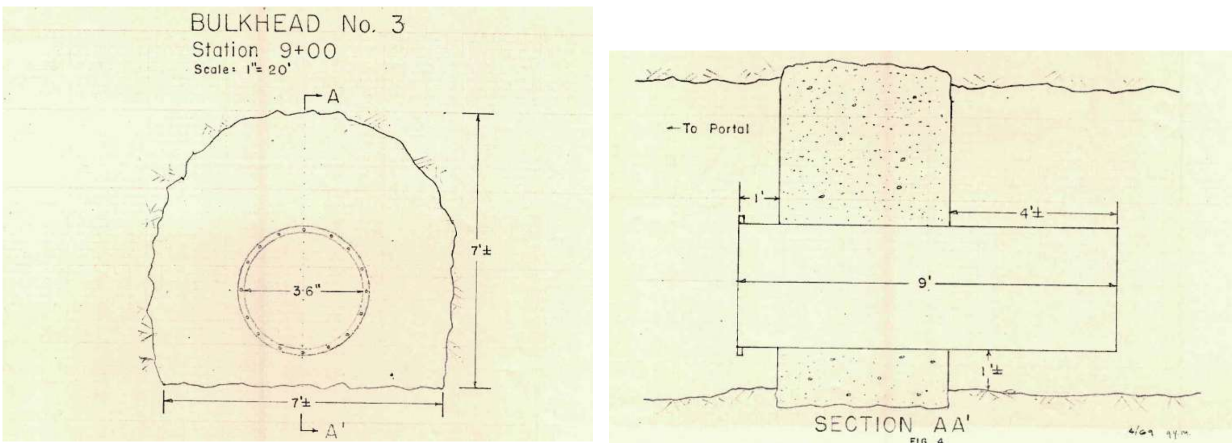


Figure 40: Schematic of Bulkhead No. 3 (STA 9+00) - From Bowles Report

Figure 41: Photograph of Bulkhead No. 1 (STA 0+30) - From Bowles Planning Report

If a fourth bulkhead is to be installed, localized chipping of the rock surface at the perimeter of the bulkhead will be required for stability and watertightness. This can be performed using powered hand tools or more sophisticated robotic demolition equipment that promotes a much higher level for worker safety, particularly during overhead work. The same equipment utilized to demolish the existing bulkheads could be used for this work, however, different tooling may be required.

During the work there would need to be a pre-entry decontamination requirement for equipment, materials, and personnel. Equipment would be wrapped similarly to what is used for watercraft. Personnel entry would need to follow a strict pre-entry decontamination procedure each day. All installed materials would need to be NSF 60 certified. Lastly, after construction decontamination of the tunnel will be required to prevent bacterial growth due to contaminants that may have been introduced during construction. Refer to Section 4.4.2 for a general discussion related to tunnel contamination.

Two approaches can be taken to construct a new bulkhead. The first option would be to perform the work "in the dry" requiring the complete drainage of the tunnel and providing adequate ventilation to allow the performance of the work. The second option would be performing the work "in the wet". This option requires a chamber to be constructed down station of Bulkhead No. 2 that is used to facilitate entrance through that bulkhead without drainage of the tunnel beyond Bulkhead No. 2. These approaches are described in further detail in the following sections.

4.2.1 Construction "In the Dry"

Once the access to the Ha'ikū Tunnel Portal is sufficiently developed, lay down/working area at the portal will be required for staging equipment, materials, and labor. At the portal, ventilation fans will be required to be set up with adequate power to operate. Ventilation requirements are 200 cfm per person within the tunnel or enough flow for a minimum air velocity of 50 fpm. For a project this magnitude it would be appropriate to size the ventilation to allow for 8 to 10 personnel at any given time. Based on an assumed maximum cross-sectional area of the tunnel at about 50 sf, the minimum air flow of 2500 cfm is likely required for work within the tunnel. For the length of tunnel and flow requirements, it would be feasible to operate the ventilation equipment using standard portable diesel generators and the fan lines would likely be required to be about 12-inches to 18-inches in diameter.

As noted in Section 4.2 above, removal of the existing bulkheads will be required to provide adequate ventilation, drainage, and access through the tunnel to facilitate the work. Additionally given the age of the bulkheads, significant deterioration of the concrete and steel penetration pipes likely exists making it a cost-effective time to remove and replace as part of the project to ensure the system is viable for the next 100 years of its service life.

For effective "in the dry" construction the following general construction sequence would be as follows:

1. Mobilization and site preparation.
2. Tunnel drainage.
3. Demolish the existing piping and bulkheads from down station to up-station. As demolition activities advance along the alignment, rock support should be installed as required sufficiently ahead of the work to create a safe and stable excavation.
4. Construct new Bulkheads starting at the up-station most bulkhead working back towards the portal. New steel piping would be installed as work progresses towards the portal. Multiple pipelines would be installed to allow greater operational control as discussed in Section 4.2.
5. Recommission tunnel following construction work.

4.2.2 Construction "In the Wet"

This construction method would be used to access the tunnel beyond Bulkhead No. 2 without requiring drainage during construction. For this construction method a temporary bulkhead would be installed down station of Bulkhead No. 2 to build a hyperbaric chamber. This chamber would serve as the access point into and out of the tunnel while maintaining the natural water pressure within the tunnel. The work in the tunnel would be performed by divers. The advantage to this method is that continuous drainage and depletion of water storage over the duration of the work would not occur. Additionally, measures may be able to be implemented to allow reactivation of the tunnel system in the event that emergency usage is required. However, reactivation would require temporary cessation of the work within the tunnel.

The anticipated general construction sequence for this "in the wet" option would be as follows:

1. Mobilization and site preparation,
2. Drain tunnel between Bulkhead No. 1 and No. 2 as required,
3. Demolish Bulkhead No. 1.

4. Install a temporary construction valve or plug within the section of 12-inch pipe immediately protruding from Bulkhead No. 2 to allow shutdown.
5. Remove steel pipe down station from the previously installed valve or plug.
6. Construct the hyperbaric chamber.
7. From within the pressurized chamber remove the steel piping and connection to the 36-inch penetration pipe.
8. Install a sealable door on the 36-inch penetration in Bulkhead No. 2 for access into and out of the tunnel.
9. Access tunnel and construct the new bulkhead.
10. Install new piping from Bulkhead No. 4 to Bulkhead No. 2.
11. Install new piping from Bulkhead No. 3 to Bulkhead No. 2, if deemed necessary (refer to discussion in Section 4.2).
12. Install a new flange on the 36-inch penetration pipe in Bulkhead No. 2 to receive two (2), or three (3), steel pipes as required.
13. Continue installation of all piping from Bulkhead No. 2 to the portal.
14. Install piping through hyperbaric chamber bulkhead, leaving the bulkhead in place for future interventions, as needed.
15. Reconstruct Bulkhead No. 1.
16. Install valving at the portal to operate each of the pipes independently.

This option is feasible; however, it is anticipated to be significantly more expensive than using "in the dry" techniques.

4.2.3 Conceptual Bulkhead Design

Conceptual bulkhead designs are presented in Appendix C and are similar to the concepts shown in the Bowles report. For efficient future use, including access for inspection, it is recommended to have three penetration types, one for access, one for the groundwater withdrawal pipeline(s) and one for a wash out to drain each compartment prior to entry as well as to provide a low-level drain to handle the inflow during inspections.

Pipeline and drain sizes should be determined based on system pressure range, design withdrawal rates and steady state rates during storage depletion. However, based on current set-up it is anticipated that the groundwater withdrawal pipelines will be 12-inches or less, depending on which compartment is being tapped. At this time, it is expected that the pipeline used to withdrawal ground water from beyond Bulkhead No. 4 would be 12-inch diameter. Pipelines used to withdrawal groundwater from the dike compartments between Bulkheads No. 2 and No. 3 and between Bulkheads No. 1 and No. 2 would be much smaller.

The drain line would be expected to be less than 12-inches, two pipes of smaller diameter could be installed if space constraints along the face of the bulkheads is realized during final design. The drain lines should be valved at each bulkhead to allow manual operation during entry.

A separate access hatch is recommended for future inspections. This hatch should have a diameter between 30-inches and 36-inches to allow person access. Square or rectangular hatches could also be considered and determined during final design to optimize bulkhead configuration.

Installation of a fourth penetration for ventilation purpose was considered but given the size of the bulkhead additional penetrations could result in significant effects on congestion when placing concrete for the bulkheads. Therefore, the design of the pipeline(s) should consider a dual function as ventilation lines during inspections. Considerations would also be made to install real-time remote reading instrumentation within each pipeline to separately monitor withdrawal rate and pressure.

4.3 Installation of Pipe from Bulkhead No. 2 to Bulkhead No. 3 (Alternative 3)

As described in Section 3.3, this option considers extending the pipeline to Bulkhead No. 3. However, as indicated in Section 4.2, the 12-inch diameter pipe that extends from the 90-degree bend at the portal through the tunnel to Bulkhead No. 2, as shown in Figure 38 above, would need to be removed to facilitate access through the tunnel and to perform the work. Therefore, to complete this work the 12-inch pipe would need to be removed from the tunnel and new piping is recommended to be installed.

As part of this option, decisions with respect to tunnel function need further consideration that will affect construction requirements. We have identified two options as follows:

1. Install one section of pipe from the 90-degree bend at the portal through Bulkhead Nos. 1, 2, and 3 and close each bulkhead such that groundwater is only withdrawn from the tunnel up station from Bulkhead No. 3. The bulkheads will be closed around each penetration to mitigate potential for inter dike compartment connection.

2. Install 2 pipelines, one extending to bulkhead No. 2 and the other extending to Bulkhead No. 3. The bulkheads will be closed around each penetration to mitigate potential for inter dike compartment connection similar to option 1. The difference being that the dike compartment between Bulkhead No. 1 and No. 2 will be tapped and allow the reported 1.5 MGD of stored water to be used at the discretion of HBWS.

For both options it appears feasible to leave all bulkheads in place. After removal of the existing pipeline, the remaining bulkheads and pipe penetrations should be inspected for deterioration and/or damage. Repairs to the bulkheads can be made at that time, which could also consist of contact grouting at the rock bulkhead interface to mitigate existing leakage, if it exists.

The two options would generally follow the same construction sequence, however, the flange at Bulkhead No. 1 and No. 2 would need to be designed and fabricated to receive two pipes versus the current configuration of one pipe. The general sequence is as follows:

1. Mobilization and site preparation.
2. Tunnel drainage.
3. Demolish the existing piping and remove flanges at Bulkhead Nos. 1 & 2
4. Install new flange on Bulkhead No. 3 and install piping back to Bulkhead No. 2.
5. Install new flange on Bulkhead No. 2 and install piping back to Bulkhead No. 1.
6. Install new flange on Bulkhead No. 1 and install piping back to the 90 degree bend at the corner. Valving should be installed on both pipes to allow shut down and opening of each pipeline individually.

4.4 Construction Risks

Risks associated with all three alternatives above exist. At a high level, the most significant risks are tunnel condition and safety, tunnel contamination, groundwater storage depletion, and lack of effectiveness of the newly constructed bulkhead. Each risk is described in the sections below.

4.4.1 Tunnel Condition and Safety

The current condition and stability of the tunnel is not known. Therefore, if major work is to be performed beyond Bulkhead No. 2 an inspection by a licensed tunneling Geologist and/or Engineer would be warranted to ensure that entry can be done safely and to determine if and where rock support is required. Given that tunnel entry has not been performed in more than 50 years, since Bowles inspection in 1969, there is potential for destabilization of rock wedges during depressurization. It is recommended that prior to initial worker entry utilization of robotic equipment to assess existing tunnel conditions and potential safety hazards is performed. Once that information is gained, decisions can be made on how safety risks could be mitigated.

4.4.2 Tunnel Contamination

Each of the alternatives that involve installation of a new bulkhead or new piping will require entry into Ha'ikū Tunnel. However, prior to executing any construction work, tunnel entry to facilitate inspection and documentation of current conditions would be required. This poses numerous challenges as it is imperative that no biological hazards be introduced into the tunnel or that in-tunnel activities would create a condition that renders water unusable, as was the case with unlined Palolo Tunnel. That tunnel was entered into during fall 2020 and since that time Total Coliform and E-coli have been detected. The cause of this condition is thought to be the disturbance of sediment within the unlined tunnel.

Since the majority of Ha'ikū Tunnel is unlined, development of a tunnel pre-entry program that includes water quality and sediment analysis at the tunnel portal would be part of the written plan. Pre-entry testing is important to determine in-tunnel water quality. Depending on the analytical results, additional investigation might be needed to identify potential surface activities at elevations higher than the portal that could be contributing to the presence of detected pathogens.

The tunnel entry and exit plan would focus on preventing the introduction of new external pathogens into the tunnel by persons, Personal Protective Equipment, and tools. Preparers of this plan must consider site location, access, and logistics. Although many of the basic practices described the plan would be similar to those employed during investigation or remediation activities at a hazardous waste site, other practices might be derived from protocols for decontamination of biohazards in laboratories or even decontamination of first responders involved with COVID-19. For these reasons, a well thought out Pre-entry and Entry Plan will require participation by several entities and should include practitioners such as a Certified Industrial Hygienist and Certified Safety Professional.

4.4.3 Groundwater Storage Depletion

Any "in the dry" construction methods used for bulkhead or piping installation within the Haʻikū Tunnel will require that the tunnel is drained. During the initial tunnel drainage and construction, storage within the dike compartments that supply groundwater to the Haʻikū Tunnel will reduce. The loss of storage and free flow mode of the tunnel will likely adversely affect groundwater flow to the Kahalu'u and Ioleka'a Streams as identified by Hirashima (1962 and 1963) during the construction of the Haʻikū Tunnel. Additionally, the loss of storage and allowing a free flow condition of the Haʻikū Tunnel during the work could affect the available groundwater supply to the Kahalu'u Tunnel. This effect is unknown as this tunnel was constructed after construction of the Haʻikū Tunnel. Consideration would need to be made to reduce groundwater withdrawal rates from the Kahalu'u Tunnel during the work to reduce storage depletion, if possible. However, it may not be possible due to the Haʻikū Tunnel outage and community demand. Given the proximity of the Luluku Stream and Luluku Tunnel to the Haʻikū Tunnel interconnectivity may also exist and should also be considered.

4.4.4 Bulkhead Effectiveness

As discussed throughout this report the dike compartments that supply groundwater to the Haʻikū Tunnel apparently extend to or are connected to dike compartments within nearby valleys where other groundwater withdrawal operations are ongoing. Due to dike connectivity combined with groundwater withdrawal in nearby valleys, it is possible that the volume of groundwater being withdrawn from these compartments does not allow groundwater levels to rise to a level where bulkheading beyond Bulkhead No. 2 would be effective. This can be explained by the pressure readings from the Haʻikū Tunnel pipeline that show there has been little to no pressure change since January 2022, whereas beginning in August 2021 withdrawal rates from the Haʻikū Tunnel have been substantially reduced. Though the pressure will likely never reach the 90 to 95 psi recorded immediately after original tunnel construction, the height of stored water would be expected to rise at withdrawal rates that are lower than the estimated recharge rates.

Section 2.6 of this report, describes how the withdrawal rate from the Kahalu'u Tunnel was increased similar in magnitude at this time. If the dike compartments that supply these tunnels are connected and the total combined withdrawal rate stayed relatively constant, then little to no pressure change in the Haʻikū Tunnel would be consistent with this. Given that it does not appear that significant groundwater is being lost from the Haʻikū Tunnel, as would likely be evinced by increased flow of the He'eia Stream, it is plausible that the dike at Bulkhead No. 2 extends higher than required to contain 100-feet of groundwater (equivalent to 43 psi pressure) which corresponds to approximately EL 650-feet. At the location of the dike associated with Bulkhead No. 2 the He'eia stream bed is above EL. 710-ft. Therefore, if the dike extends to, or nearly to, the surface it may have the ability to impound groundwater up to an elevation that would result in about 70 psi of groundwater pressure in the dike compartment(s) and the Haʻikū Tunnel. Figure 42 illustrates the potential storage height developed by the dike at Bulkhead No. 2. As shown, the dike at Bulkhead No. 2 most likely extends up to at least elevation 650-feet as a current pressure of 43 psi, which is equivalent to about 100-feet of water head, is observed. It is also shown that an additional 60-ft of water head could be realized if that dike extends up to elevation 710-feet which Is the approximate bottom of the stream bed elevation. This 160-feet of water head would result in a pressure of about 70 psi.

Following the paragraphs above it is plausible that an additional bulkhead will not result in additional storage height due to the volume of groundwater that is being extracted from the dike compartments in the Haʻikū Valley and nearby valleys. A recharge study and comparison to groundwater withdrawal rates from the dike compartments could provide significant insight with respect to the overall water balance. Additionally operational testing of the groundwater withdrawal systems could be performed to test storage potential.

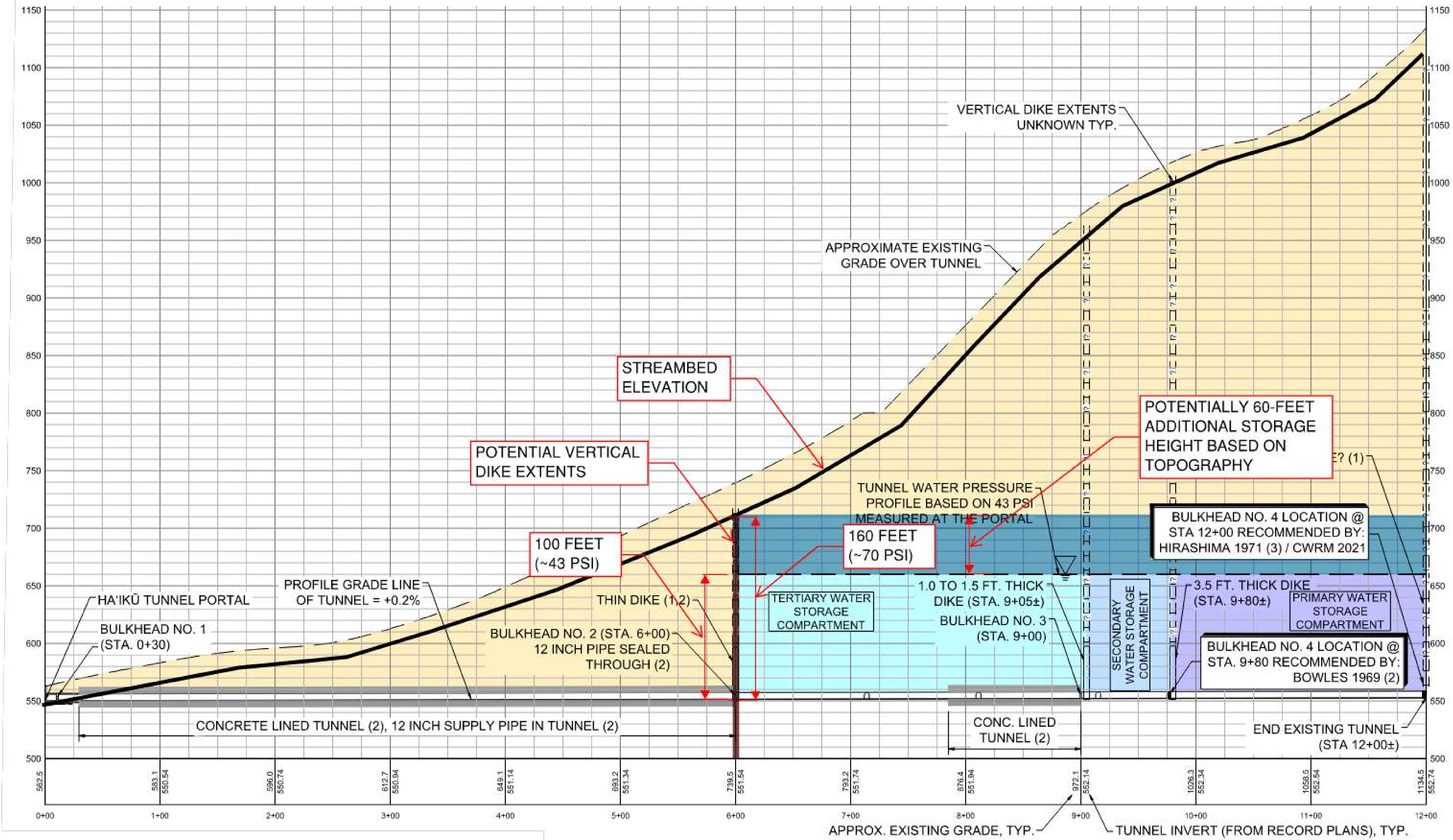


Figure 42: Potential available storage height behind Bulkhead No. 2

4.5 Summary

The preceding narrative presented a wide array of challenges, solutions, and risks associated with conceptual alternatives to improve groundwater storage within the dike system that supplies water to Ha'ikū Tunnel, as noted in the following:

- The logistics associated with performing major construction works at the Ha'ikū Tunnel will be extremely difficult. Access to the site is via Ha'ikū Road through several residential neighborhoods on the outskirts of Kaneohe. Roads are relatively narrow and ill-suited for a significant volume of heavy traffic so improvements will be needed to facilitate construction traffic.

- The narrow hiking path that leads to the tunnel portal would require significant improvements to allow staging and construction equipment access. Due to the expected modifications, it is anticipated that a rigorous permitting process may be necessary.

- Over 50 years have elapsed since the tunnel was entered. The condition of the tunnel and rock stability is unknown. Prior to progressing any design work, inspection of the tunnel initially by robotic means followed by in-person inspection by an experienced and licensed tunnel geologist or engineer would be required.

- Robust pre-entry and post-entry decontamination protocols will need to be established during any inspection and construction work. This will require participation by several entities and should include practitioners such as a Certified Industrial Hygienist and Certified Safety Professional.

- Fourth bulkhead construction is hindered by existing Bulkheads No. 1, No. 2 and No. 3 all of which present significant restrictions associated with personnel access, material transportation, and ventilation during work.

- New bulkhead design needs to account for three penetration types, one for access, one for the groundwater withdrawal pipeline(s) and one for a wash out to drain each compartment prior to entry as well as to provide a low-level drain to handle the inflow during inspections and real-time remote read instrumentation to measure in-tunnel pressure.

- "In the Dry" and "In the Wet" construction methods could be implemented to accomplish new bulkhead construction, each having their own technology and skilled labor availability challenges. Additionally, existing bulkhead(s) removal would be required, depending on method selection.

- "In the Dry" construction would demolish the existing piping and bulkheads from down station to up-station followed by new bulkhead installation, starting at the up-station most bulkhead working back towards the portal. New steel piping would be installed as work progresses towards the portal. Multiple pipelines would be installed to allow greater operational control.

- "Construction in the wet" by specially trained and experienced divers could be implemented. This method would require dewatering of the tunnel between Bulkhead No. 1 and No. 2, installation of a temporary bulkhead down station of Bulkhead No. 2 to allow installation of a hyperbaric chamber that would facilitate access into and out of the tunnel while maintaining the natural water pressure within the tunnel.

  - "In the Wet" components include: Demolish Bulkhead No. 1; construct the new bulkhead; install new piping from Bulkhead No. 4 to Bulkhead No. 2; install new piping from Bulkhead No. 3 to Bulkhead No. 2; reconstruct Bulkhead No. 1; all new piping would have valving at the portal to operate each of the pipes independently.

  - "In the Wet" construction work is typically more expensive and poses more risks as compared to conventional "In the Dry" methods.

- Extending a new pipeline(s) from Bulkheads No. 2 to Bulkhead No. 3 would not require bulkhead demolition but would require removal of the existing 12-inch pipe. Depending on configuration, one or 2 new pipelines would be installed, depending on the desire to discretely control flow between Bulkheads No. 2 and No. 3

- "In the dry" construction methods within the Haʻikū Tunnel will require draining of the tunnel. The loss of storage and free flow mode of the tunnel will likely adversely affect groundwater flow to the Kahalu'u and Ioleka'a Streams.

  - Loss of storage and allowing a free flow condition of the Haʻikū Tunnel during the work could affect the available groundwater supply to the Kahalu'u Tunnel. This effect is unknown as this tunnel was constructed after construction of the Haʻikū Tunnel.

  - Consideration would need to be made to reduce groundwater withdrawal rates from the Kahalu'u Tunnel during the work to reduce storage depletion, if possible. However, it may not be possible due to the Haʻikū Tunnel outage and community demand.

- As discussed throughout this report the dike compartments that supply groundwater to the Haʻikū Tunnel apparently extend to or are connected to dike compartments within nearby valleys where other groundwater withdrawal operations are ongoing. Further, the tunnel construction documents indicated a potential storage pressure of 90 to 95 psi, only half of which appears to be currently achievable. Due to dike connectivity combined with groundwater withdrawal in nearby valleys, it is possible that the volume of groundwater being withdrawn from these compartments does not allow groundwater levels to rise a level where bulkheading beyond Bulkhead No. 2 will be effective.

5 CONSTRUCTION COST AND SCHEDULE

5.1 Introduction

All of the identified construction alternatives represent moderate to significant financial resources and effort, requiring mobilization of a skilled labor force to construct. Site access is through/adjacent to residential neighborhoods that will restrict permitted working hours and noise levels. For purposes of preliminary evaluation, a single 10-hour shift limited to normal working days is anticipated for construction activities. Activities within the tunnel not requiring substantial supporting traffic/material deliveries (such as demolition) could potentially operate on double 10-hour shifts, provided appropriate noise restrictions can be adhered to for outside supporting equipment; ventilation fans and generators in particular generally require noise attenuation for nighttime operations near residential neighborhoods.

The construction alternatives identified during this preliminary study require significant in-tunnel activities ranging from tunnel reinforcement work to bulkhead demolition, reconstruction and placement of new pipes and valves. Also, selection of work method, in-the-dry or in-the-wet, will be required. For either scenario, replacement of the existing piping is considered. A high-level evaluation of the "in the wet" alternative indicates costs exceeding $40M and a significantly lengthened construction duration (approximately 36-48 months) due to the inherent inefficiency of this type of operation. There are also considerably elevated safety risks and a severely limited workforce available with the requisite qualifications and experience. As both the risks and costs of this methodology are far higher, further consideration does not appear warranted.

Construction of a new parallel tunnel is also a significant cost and still requires decommissioning of the existing tunnel. A preliminary cost estimate of this alternative exceeded $20M and has a lengthy schedule duration as well.

5.2 Engineer's Opinion of Probable Cost

Based on the report findings three alternatives were selected for development of the "Engineer's Opinion of Probable Cost" (EOPC), which are Alternatives 2, 3, and 4. Details associated with each EPOC are presented below.

5.2.1 Alternative 3

An EOPC for Alternative 3 was developed to a more detailed Class 4 (Study or Feasibility) level. This includes a project schedule (Figure 43) and more granular consideration of labor, equipment, materials and contractor indirect/overhead costs. With the conceptual level of design at this stage, the Alternative 3 EOPC still contains a significant amount of uncertainty.

Significant considerations for this Alternative 3 EOPC include:

- 7-person crew with 2 supervisory personnel working 10 hour shifts 4 days per week.
- Industrial hygienist to minimize potential for bacterial or other contamination of the tunnel.
- Allowance for tunnel safety and access/material handling requirements.
- As the estimate was developed, it became apparent that the cost (and risks) of working through the existing bulkheads appears to outweigh the benefits of leaving in place. This estimate therefore considers removal and replacement of the existing Bulkheads #1 and #2 as part of the scope. It is recommended that if this alternative were to be advanced to a bidding stage, bidders should be allowed the option to remove and replace the existing bulkheads as part of the Contract Documents.
- Costs of lost potable water supply due to taking the tunnel off-line for construction were <u>not included</u> in this or any other cost estimate.

The Alternative 3 EOPC is $7.3 million, refer to Appendix E for estimate details.

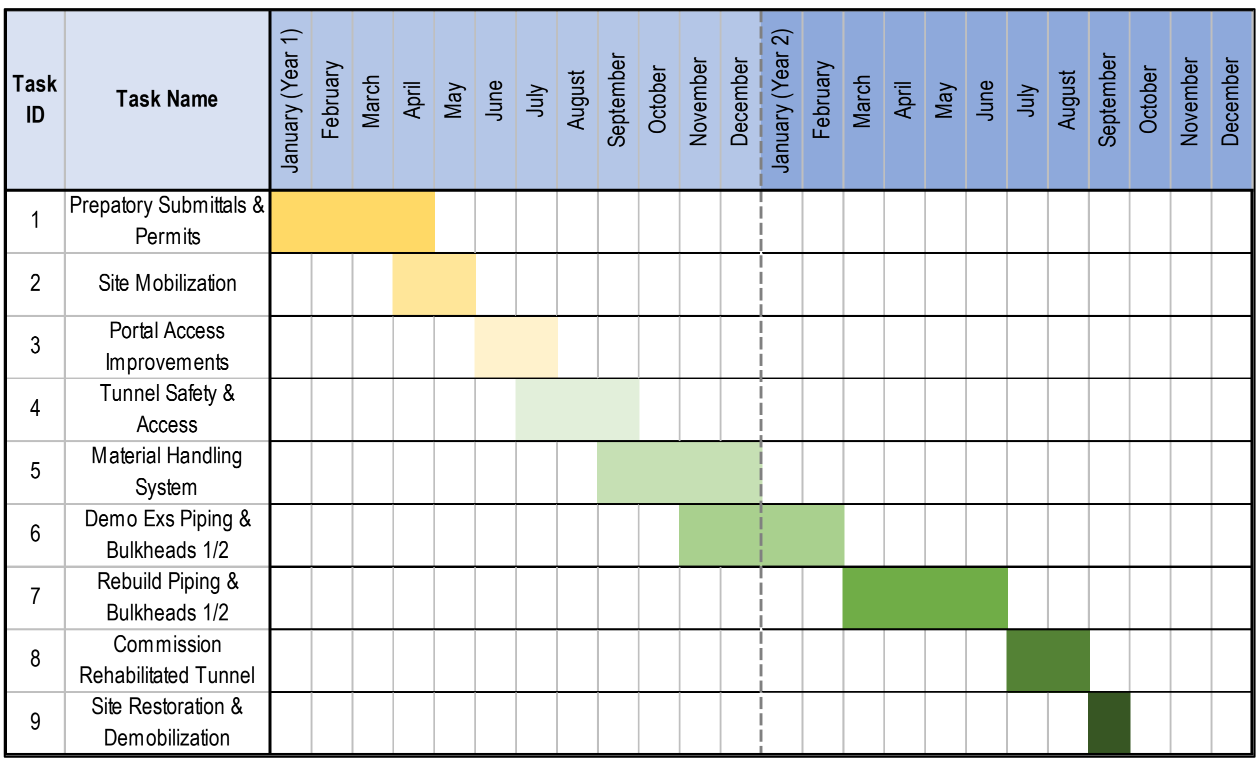


Figure 43: Alternative 3's Estimated Project Schedule

5.2.2 Alternative 2

As Alternative 2 is very similar to Alternative 3, requiring only one additional bulkhead and a short length of additional piping/valving & monitoring items, a similar estimate can be readily developed for this Alternative. The Alternative 2 EOPC is estimated as $8.7 million, details are also provided in Appendix E.

5.2.3 Alternative 4

Alternative 4 costs were evaluated at a Class 5 (Concept Screening) level. A significant factor in this estimate is to what level will the existing tunnel is decommissioned. Decommissioning could range from simply closing the existing valving to removal of the existing infrastructure and backfilling/cutoff grouting the tunnel completely to minimize leakage potential. For the purposes of this estimate, a moderate initial decommissioning effort would be undertaken, and some leakage tolerated. Alternative 4 EOPC is $26 million, a summary of considered items and costs are provided in Appendix E.

5.2.4 Summary

A summary of the EPOC for each alternative is presented in Table 10 below. Given that this is a feasibility level study a variance of -30% to +50% should be expected on the cost. An estimated construction duration is also provided for each alternative.

Table 10: Engineer's Opinion Probable Cost Summary

Option	EOPC	Estimate Range		Construction Schedule Duration (Months)
		(Low)	(High)	
Alt 3 –Re-pipe	$7.3M	$5M	$11M	18-21
Alt 2 – Extended Re-pipe	$8.7M	$6M	$13M	21-24
Alt 4 – New Tunnel	$26.0M	$13M	$52M	24-36

"In the dry" construction offers the lowest-risk, lowest cost, and shortest schedule options. The primary downside of "in the dry" is the need to have the tunnel in free-flowing mode, thus draining the reservoir during in-tunnel work. Constructing a parallel tunnel minimizes the duration of "in the dry" work, however at significant cost increase and extension of overall project schedule.

6 CONCLUSIONS AND RECOMMENDATIONS

This engineering study has examined numerous available historical records and reports in an attempt to understand the existing condition of the tunnel and surrounding hydrogeology for context in evaluating the feasibility of installation of a fourth bulkhead within Haʻikū Tunnel. Water Budget Studies and documented stream flow measurements have demonstrated that the dike compartments supplying groundwater to the Haʻikū Tunnel either extend into nearby valleys or are hydraulically connected to dike compartments in those valleys. It is recommended that additional hydrogeologic studies be performed to assess the interconnectivity associated with the dike compartments. That study, coupled with the forthcoming updated water budget model and recharge estimate may be able to provide additional insight with regards to recharge and interconnectivity associated with the dike compartments providing groundwater to the water supply tunnels and wells within the region.

Installation of a fourth bulkhead within the Haʻikū tunnel requires a considerable investment of resources, incurs substantial risks and ultimately may not be able to achieve any substantial improvement in the storage capacity. With historical records indicating a potential storage pressure of the current tunnel configuration nearly twice what is currently being measured, additional storage capacity would appear possible within the compartments supplying the tunnel but is not being achieved. It is unclear whether additional groundwater storage is not occurring because the groundwater is either leaking out of the dike compartments and/or being extracted from other interconnected existing tunnels and/or wells. Providing additional time for recharge to occur and potentially rebuild storage to a larger fraction of what the existing tunnel configuration originally was capable of maintaining appears to be the best course of action given current understanding of the Haʻikū tunnel conditions.

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APPENDIX A

INTERPRETATION OF EXISTING CONDITIONS

Table A-1: Summary of Haʻikū Tunnel Features

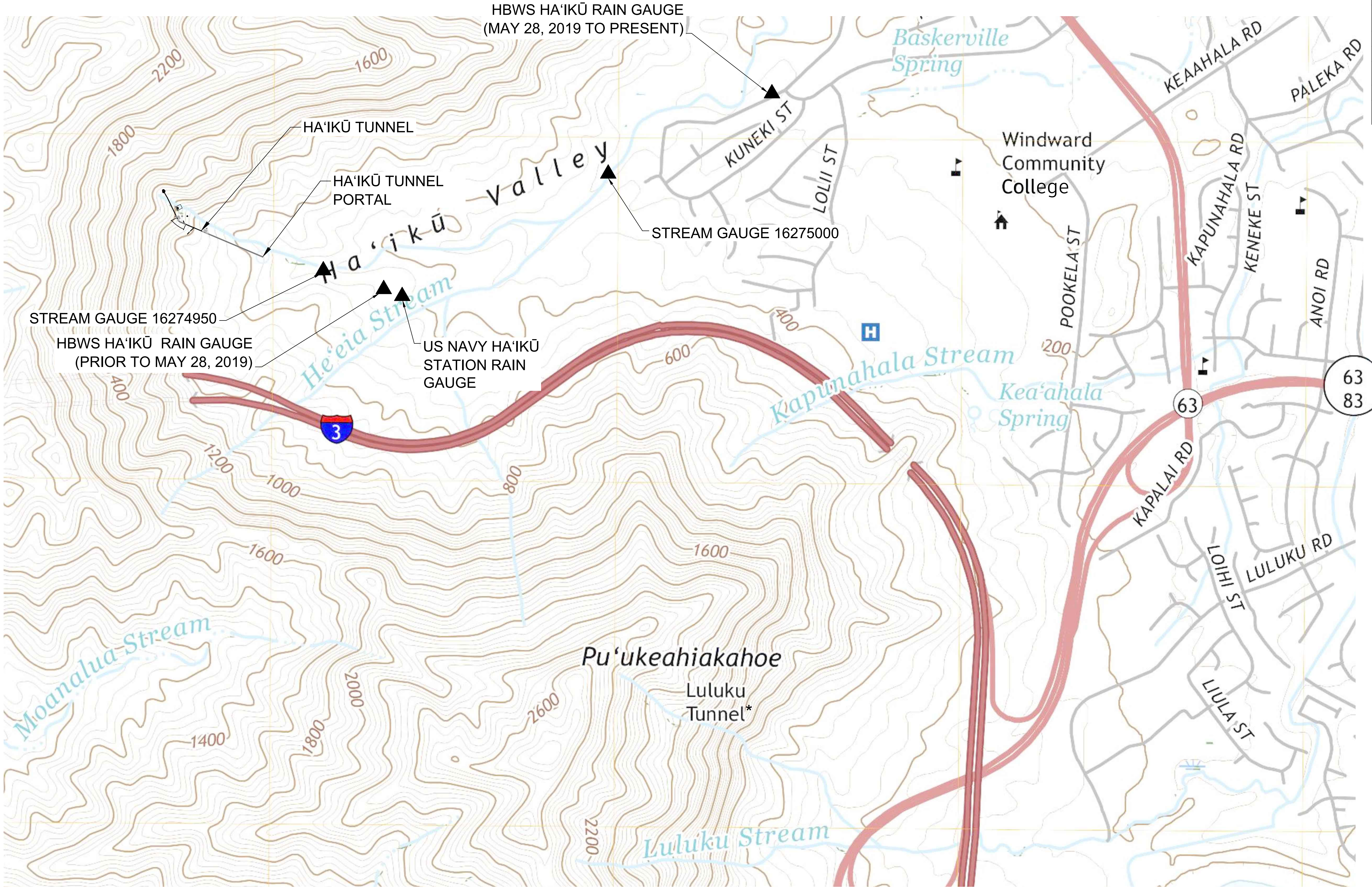
(Reference: Drawing N-00805, HBWS Haiku Tunnel Sketch 1966, Haiku Tunnel Investigation Sketch 1969, Bowles 1969)

Station	Tunnel Feature	Bulkhead (BH)	Remarks
0+30	--	BH-1 (20-in thick)	Concrete lining from STA 0+00 to STA 6+00
6+00	Thin dike (thickness not found)	BH-2 (3-ft thick)	
7+14	15.5-ft long lateral tunnel	--	--
8+11	26-ft long lateral tunnel	--	Concrete lining from STA 8+11 to STA 9+00
8+60	Tunnel alignment changed 42 degrees in a northerly direction	--	
9+00	--	BH-3 (~ 4-ft thick) Based on the provided information it is not known if this bulkhead is sealed or if groundwater may freely pass through the 36-in diameter pipe installed through it.	
9+80	3.5-ft thick dike	--	--
~12+00	End of tunnel	--	--

Table A-2: Geology and Flow Encountered during Construction

(Reference: Drawing N-00805, HBWS Haiku Tunnel Sketch 1966, Haiku Tunnel Investigation Sketch 1969, Bowles 1969)

Station	Geology	Discharge	Bulkhead (BH)	Remarks
6+00	A first thin dike was penetrated (thickness not found)	3 mgd	BH-2 constructed at STA 6+00	--
6+00 to 7+00	--	Dropped to 1.5 mgd at STA 7+00	--	--
7+00 to 9+00	thin dikes penetrated several times	Remains same as 1.5 mgd	BH-3 constructed at STA 9+00	Tunnel orientation change at STA 8+60
9+80	A thick dike of 3.5' penetrated	Remains the same as 1.5 mgd		??
9+80 to 11+78	Pahoehoe Lava (low permeability)	Increased steadily from 1.5 to 6.0 mgd		??
11+78	A dike was originally reported at STA 11+78. A study prior to the Bowles investigation found that it is a dense aa flow crossing at a slight dip.	6.0 mgd		??
11+78 to 12+00	Broken lava blocks/clinker material	Rapid increase in flow from 6 mgd at STA 11+78 to 11.3 mgd at STA 12+00 (peak flow)		Bowles investigation concluded that the last 20-feet was excavated through clinker. Bowles hypothesized that the sudden change in permeability at STA 11+78 and rapid increase in flow (from 6 to 11.3 mgd) likely gave the impression of taping a dike compartment at STA 12+00.
~12+00	Termination of tunnel - tunnel head	??		



LOCATION PLAN

SCALE:1"=500'

INDEX OF FIGURES	
FIGURE	TITLE
1	LOCATION PLAN AND INDEX OF FIGURES
2	TUNNEL PLAN - EXISTING CONDITIONS
3	THEORIZED WATER STORAGE COMPARTMENTS - PLAN VIEW
4	TUNNEL PROFILE - EXISTING CONDITIONS
5	THEORIZED WATER STORAGE COMPARTMENTS - PROFILE VIEW

NOTES:

(1) TOPO MAP PRODUCED BY USGS.

*TUNNEL ALIGNMENT NOT SHOWN.

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630 S. BERETANIA ST.
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PROJECT NUMBER
HAʻIKU TUNNEL BULKHEAD
PRELIMINARY ENGINEERING STUDY

FIGURE/PLATE TITLE
LOCATION PLAN AND
INDEX OF FIGURES

FIGURE/PLATE
FIG.1

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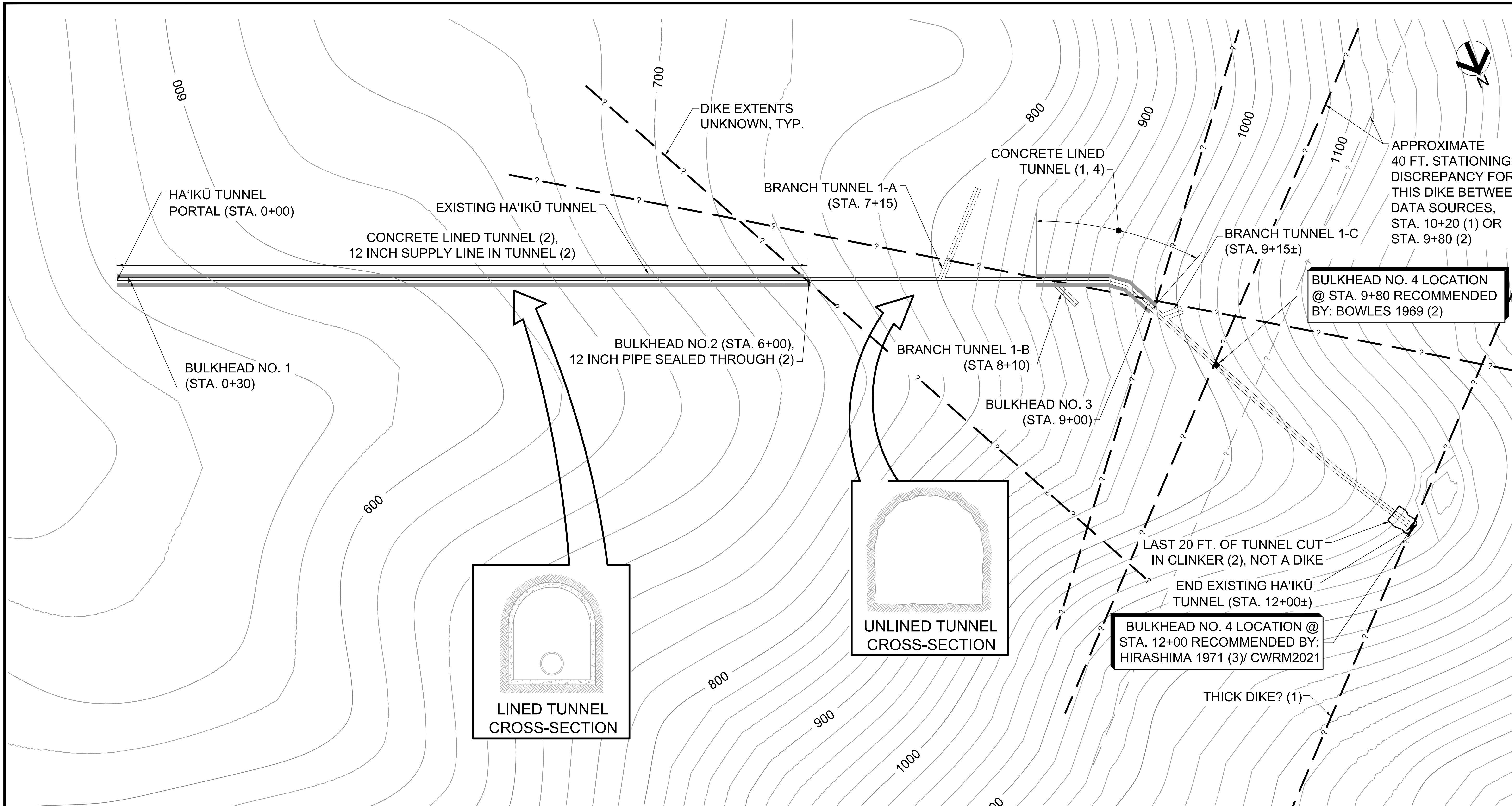

EXISTING CONDITIONS INFORMATION OBTAINED FROM THE FOLLOWING SOURCES:

(1) BOARD OF WATER SUPPLY 1940 CONSTRUCTION AS-BUILT RECORDS.

(2) "HA'IKŪ TUNNEL STUDY" FOR BOARD OF WATER SUPPLY BY S.P. BOWLES 1969.

(3) "TUNNELS AND DIKES OF THE KO'OLAU RANGE....", G.T. HIRASHIMA, 1971.

(4) ROCK WAS OBSERVED TO BE RELATIVELY DRY DURING TUNNEL CONSTRUCTION IN THIS ZONE PER BOWLES' REPORT

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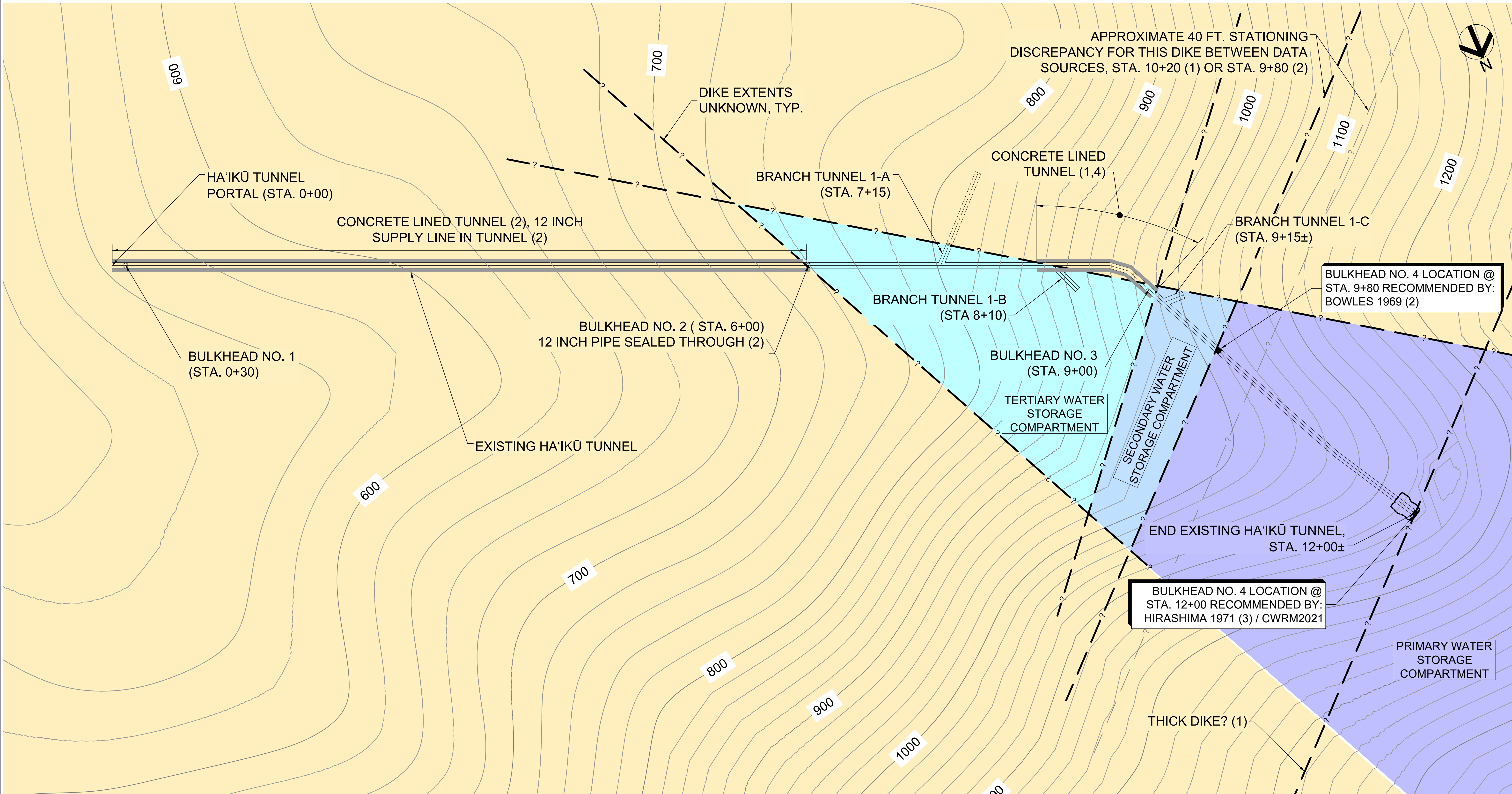
FIGURE/PLATE TITLE: TUNNEL PLAN EXISTING CONDITIONS

FIGURE/PLATE: FIG.2



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(4) ROCK WAS OBSERVED TO BE RELATIVELY DRY DURING TUNNEL CONSTRUCTION IN THIS ZONE PER BOWLES' REPORT.

0 40' 80'

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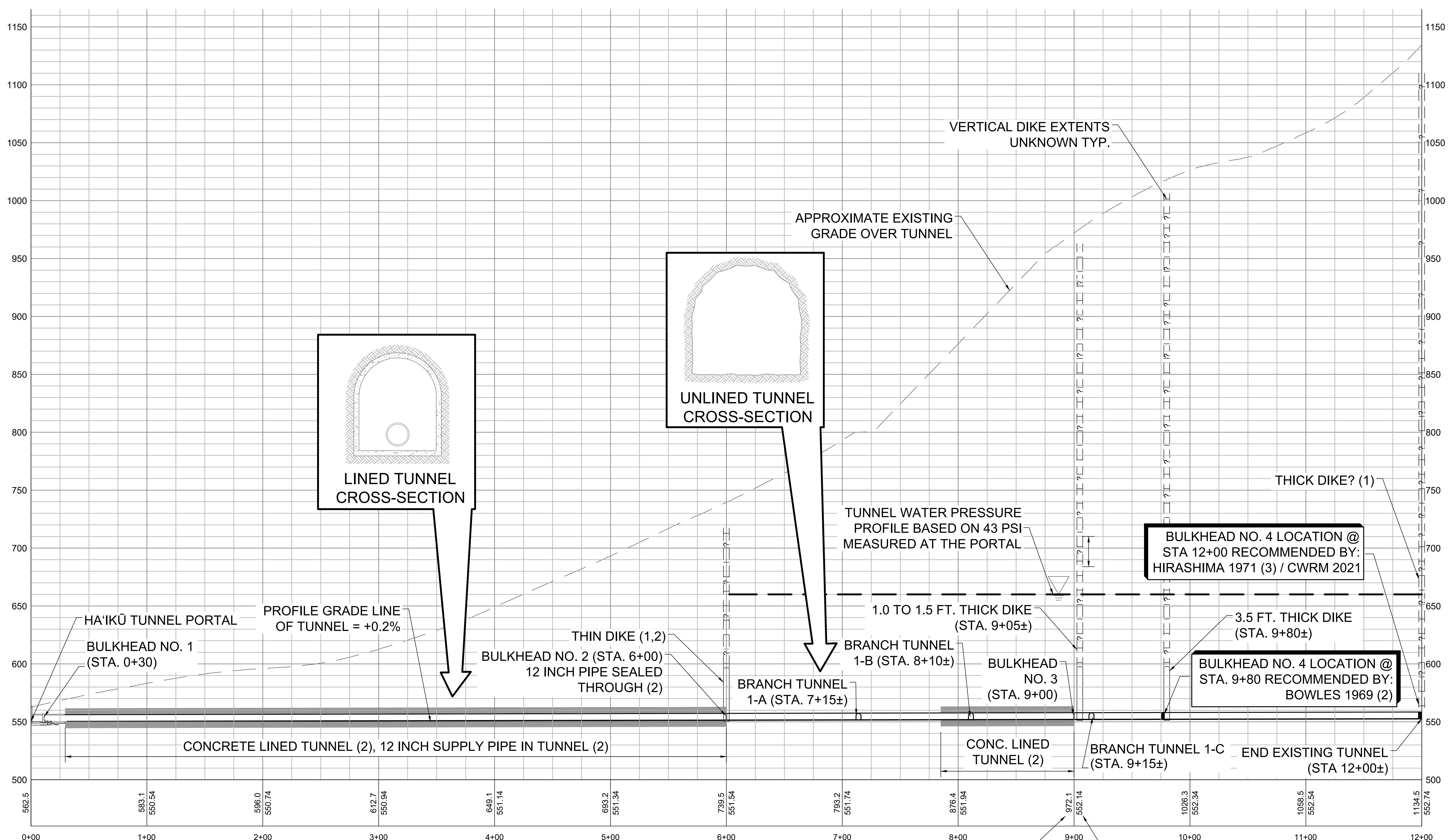
FIGURE/PLATE TITLE: THEORIZED WATER STORAGE COMPARTMENTS PLAN VIEW

FIGURE/PLATE: FIG.3



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(3) "TUNNELS AND DIKES OF THE KO'OLAU RANGE....", G.T. HIRASHIMA, 1971.

0 40' 80'

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PRELIMINARY ENGINEERING STUDY

FIGURE/PLATE TITLE
TUNNEL PROFILE
EXISTING CONDITIONS

FIGURE/PLATE
FIG.4

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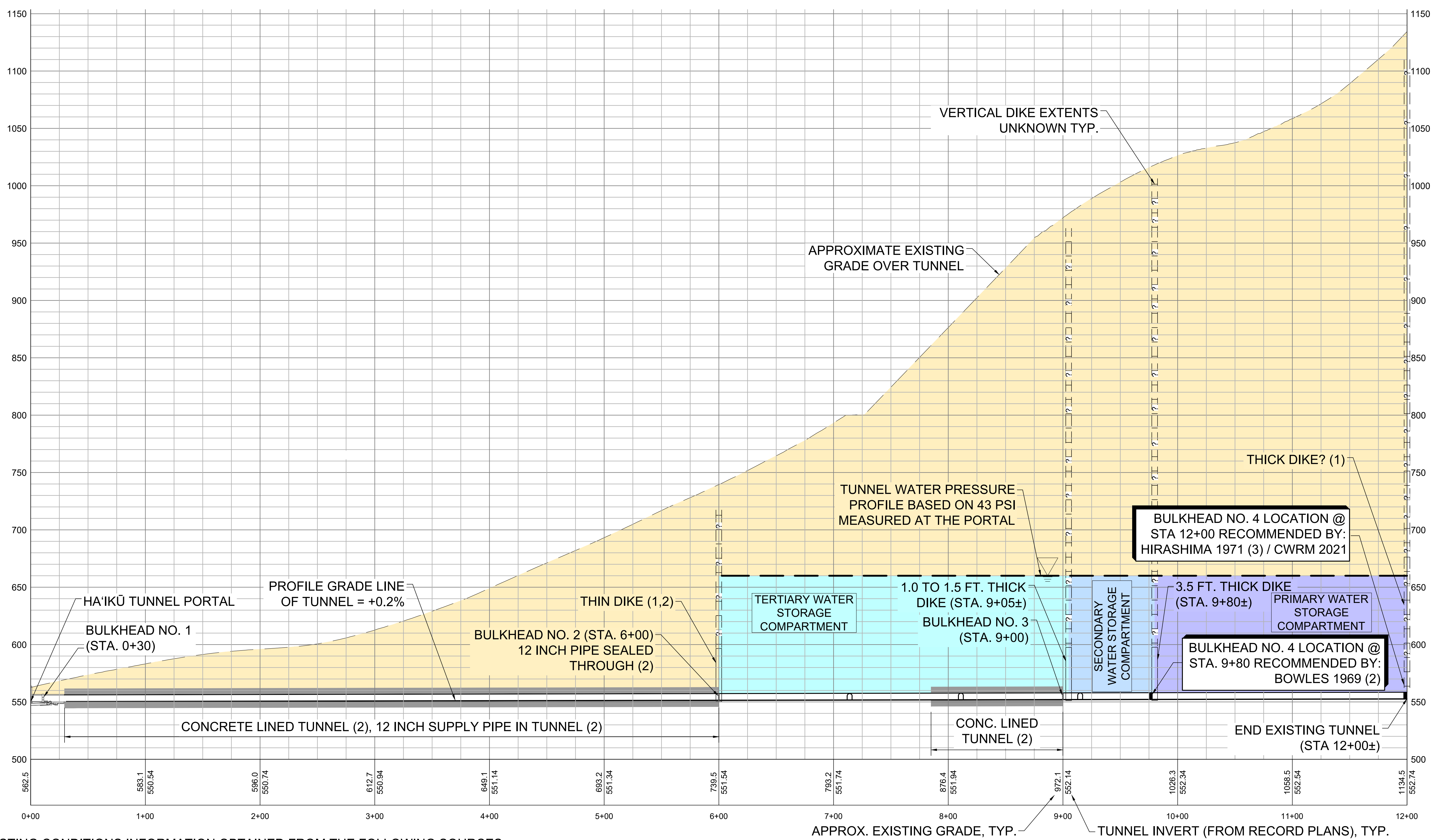

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0 40' 80'

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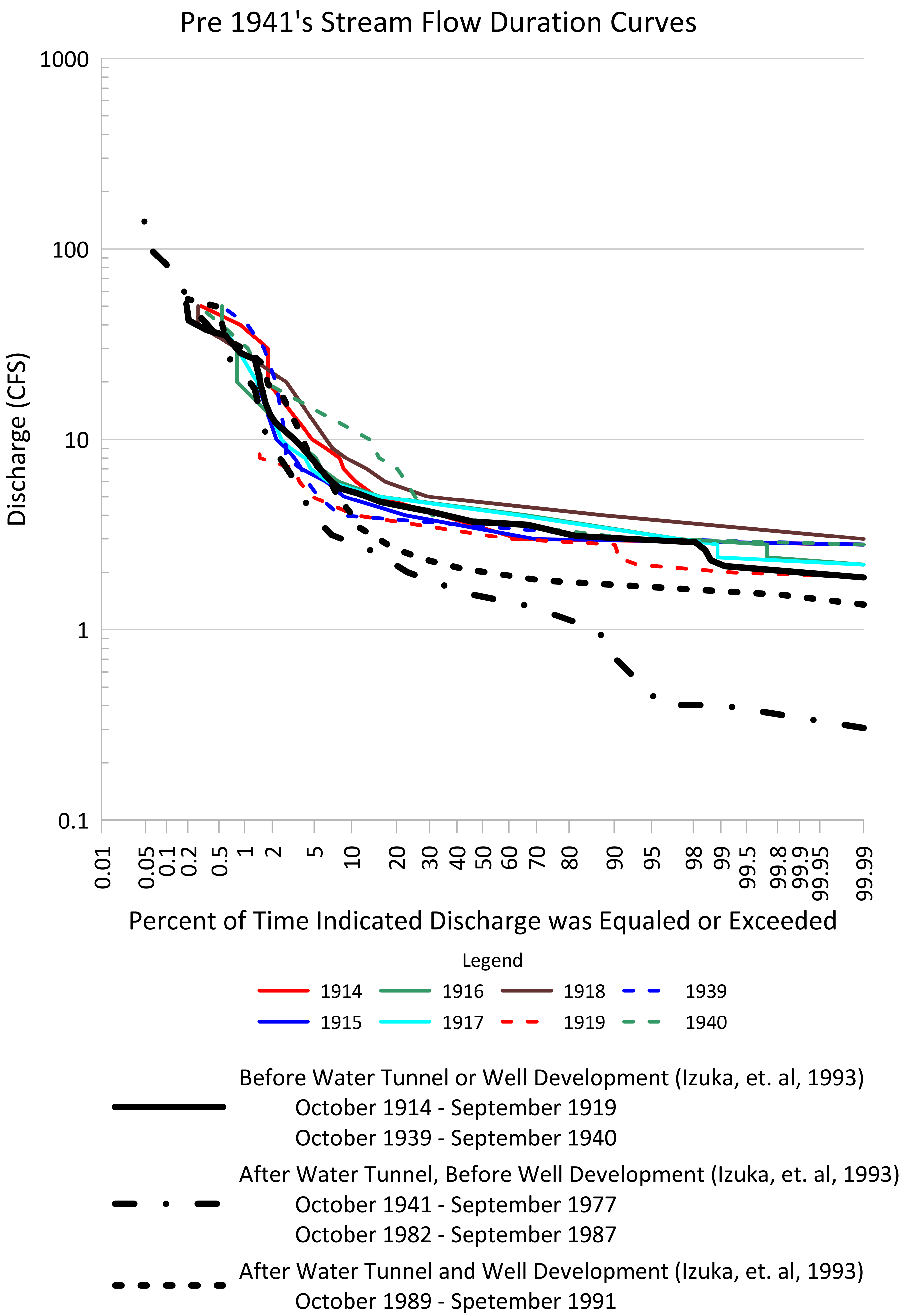
PRELIMINARY ENGINEERING STUDY

FIGURE/PLATE TITLE
THEORIZED WATER STORAGE COMPARTMENTS PROFILE VIEW

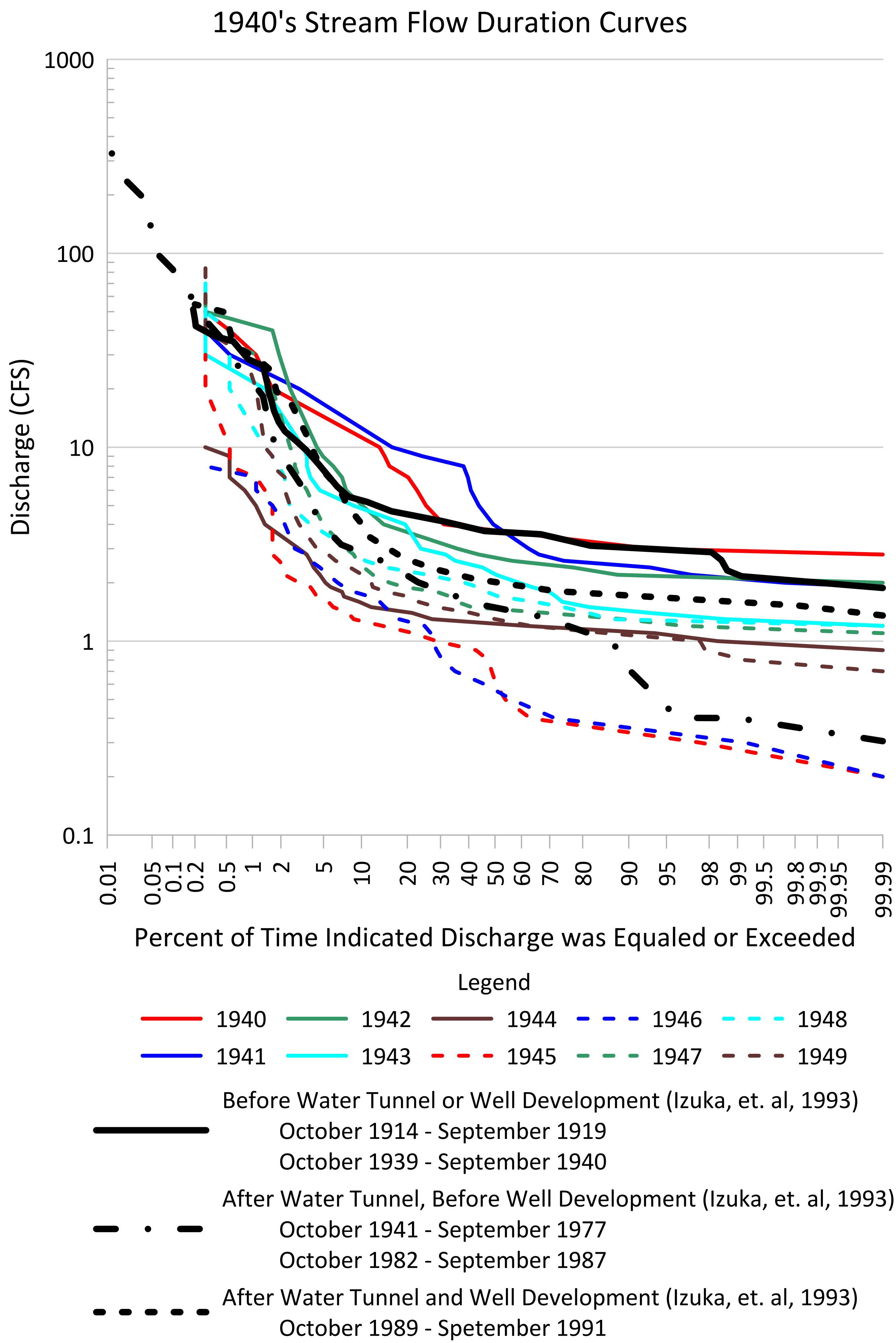
FIGURE/PLATE
FIG.5

APPENDIX B

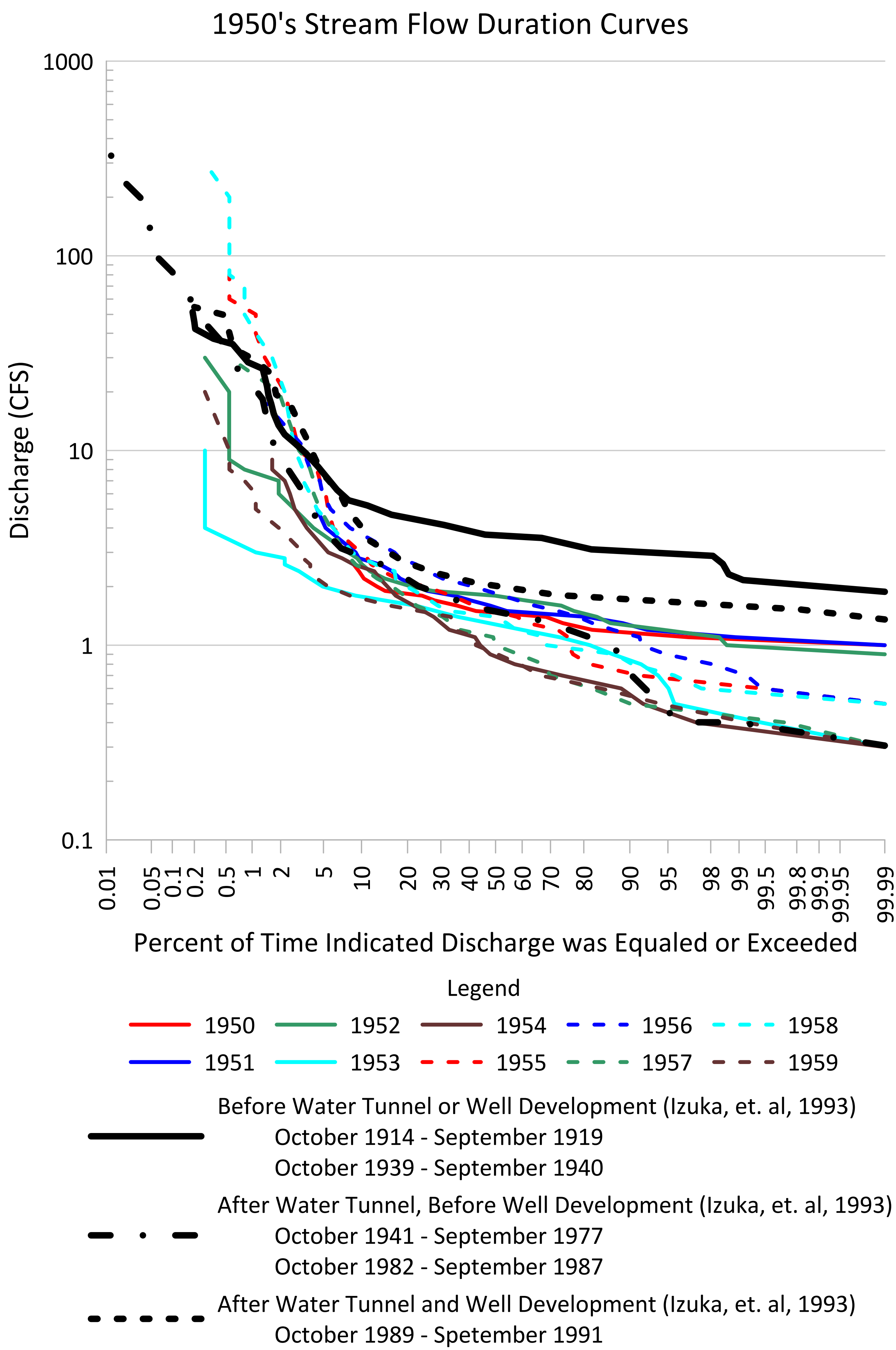
He'eia Stream Flow Duration Curves



Pre 1941's Stream Flow Duration Curves
1000
100
10
1
0.1
Discharge (CFS)
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.5
99.8
99.9
99.95
99.99
Percent of Time Indicated Discharge was Equaled or Exceeded
Legend
1914
1916
1918
1939
1915
1917
1919
1940
Before Water Tunnel or Well Development (Izuka, et. al, 1993)
October 1914 - September 1919
October 1939 - September 1940
After Water Tunnel, Before Well Development (Izuka, et. al, 1993)
October 1941 - September 1977
October 1982 - September 1987
After Water Tunnel and Well Development (Izuka, et. al, 1993)
October 1989 - Spetember 1991



1940's Stream Flow Duration Curves
Discharge (CFS)
1000
100
10
1
0.1
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.5
99.8
99.9
99.95
99.99
Percent of Time Indicated Discharge was Equaled or Exceeded
Legend
1940
1941
1942
1943
1944
1945
1946
1947
1948
1949
Before Water Tunnel or Well Development (Izuka, et. al, 1993)
October 1914 - September 1919
October 1939 - September 1940
After Water Tunnel, Before Well Development (Izuka, et. al, 1993)
October 1941 - September 1977
October 1982 - September 1987
After Water Tunnel and Well Development (Izuka, et. al, 1993)
October 1989 - Spetember 1991


1950's Stream Flow Duration Curves
Discharge (CFS)
1000
100
10
1
0.1
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.5
99.8
99.9
99.95
99.99
Percent of Time Indicated Discharge was Equaled or Exceeded
Legend
1950
1952
1954
1956
1958
1951
1953
1955
1957
1959
Before Water Tunnel or Well Development (Izuka, et. al, 1993)
October 1914 - September 1919
October 1939 - September 1940
After Water Tunnel, Before Well Development (Izuka, et. al, 1993)
October 1941 - September 1977
October 1982 - September 1987
After Water Tunnel and Well Development (Izuka, et. al, 1993)
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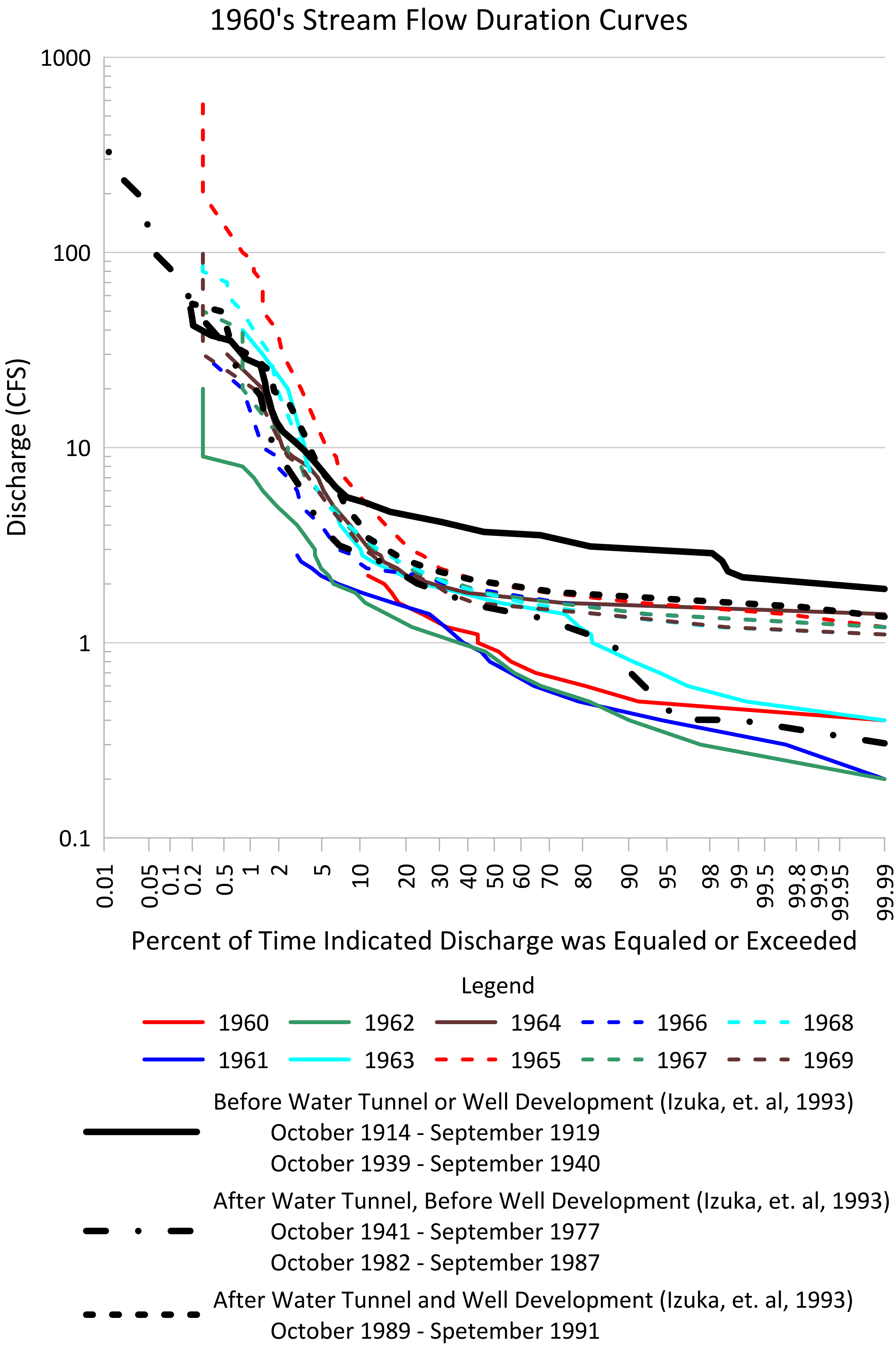
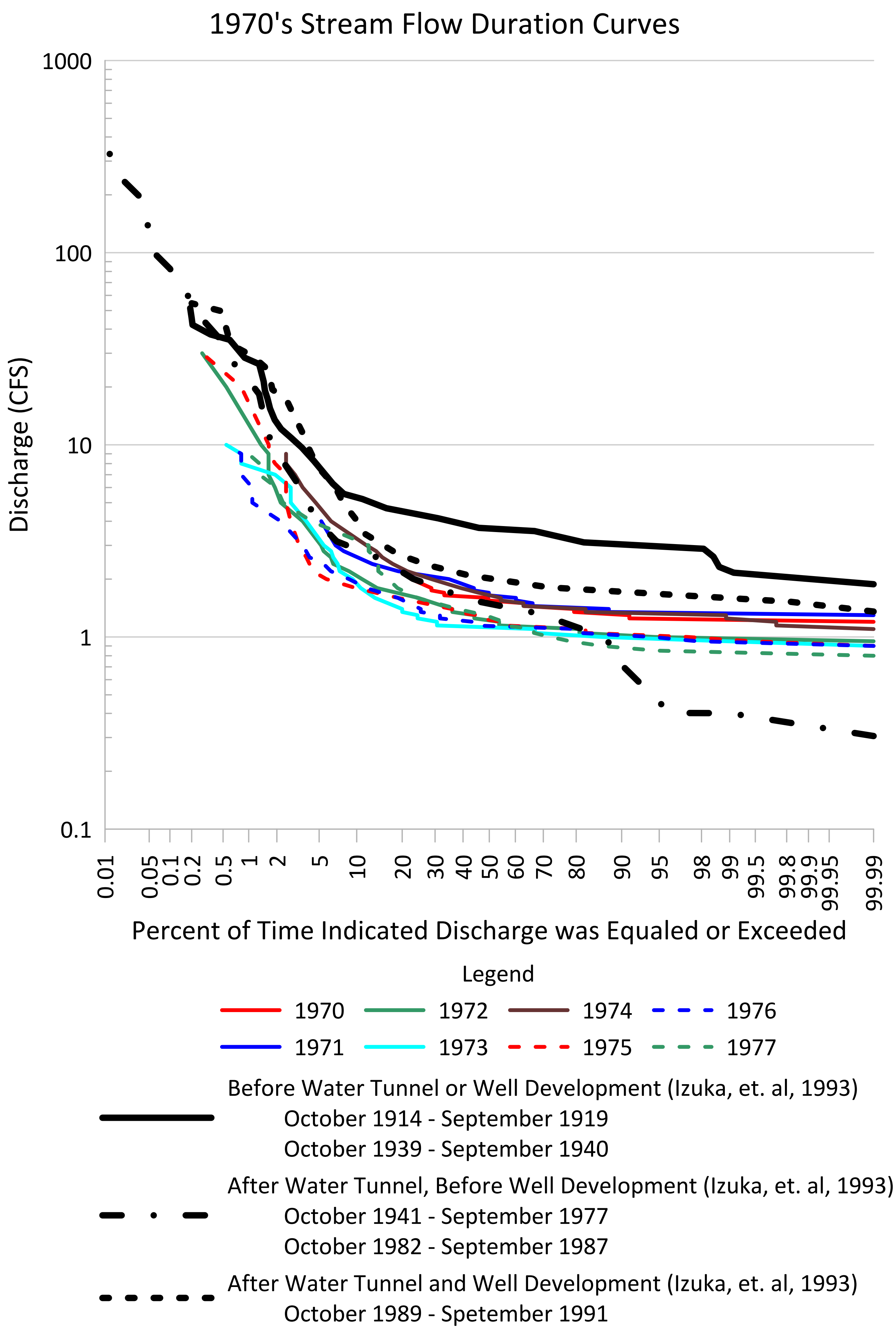
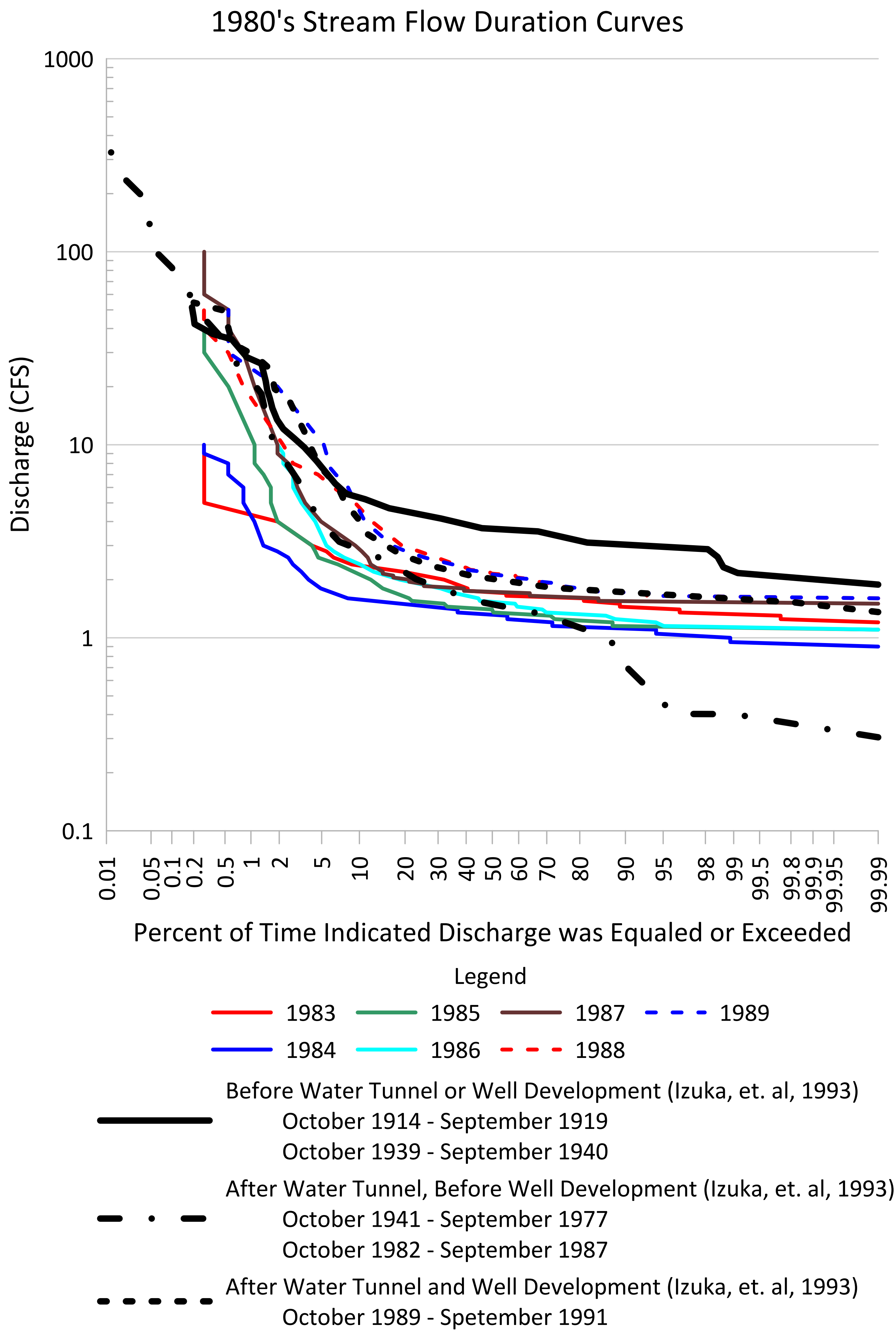
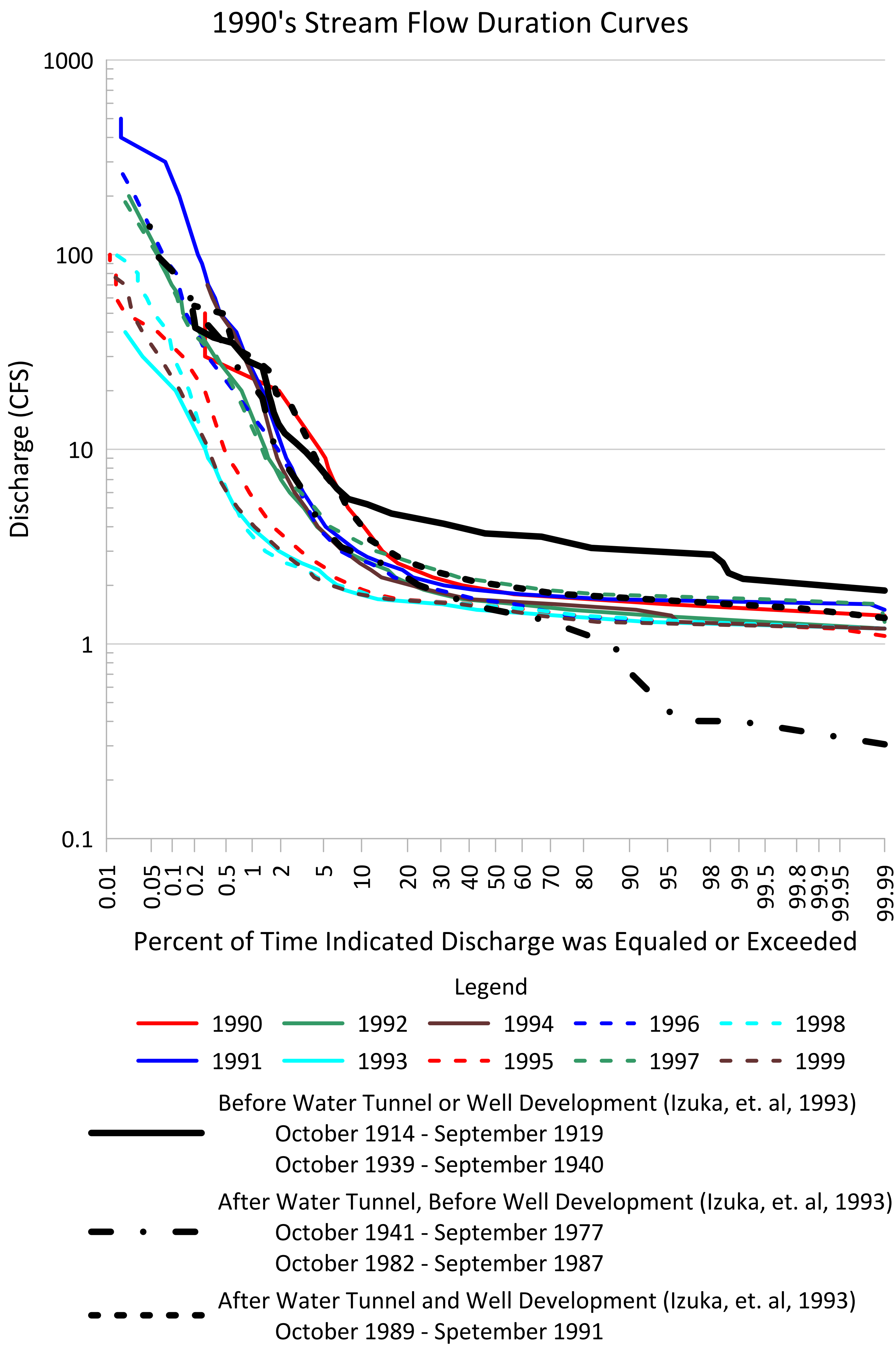
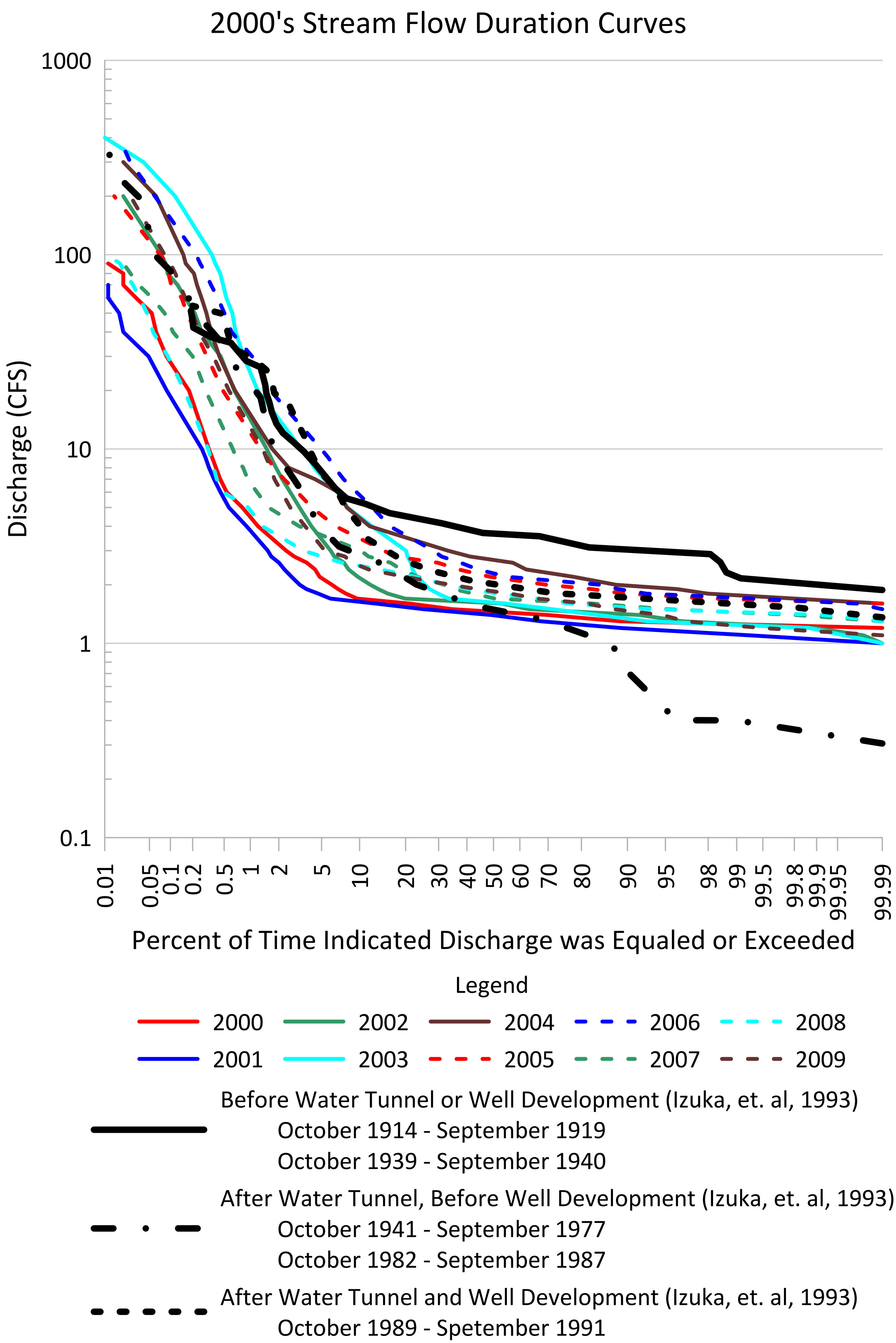

1960's Stream Flow Duration Curves
Discharge (CFS)
1000
100
10
1
0.1
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.5
99.8
99.9
99.95
99.99
Percent of Time Indicated Discharge was Equaled or Exceeded
Legend
1960
1962
1964
1966
1968
1961
1963
1965
1967
1969
Before Water Tunnel or Well Development (Izuka, et. al, 1993)
October 1914 - September 1919
October 1939 - September 1940
After Water Tunnel, Before Well Development (Izuka, et. al, 1993)
October 1941 - September 1977
October 1982 - September 1987
After Water Tunnel and Well Development (Izuka, et. al, 1993)
October 1989 - Spetember 1991

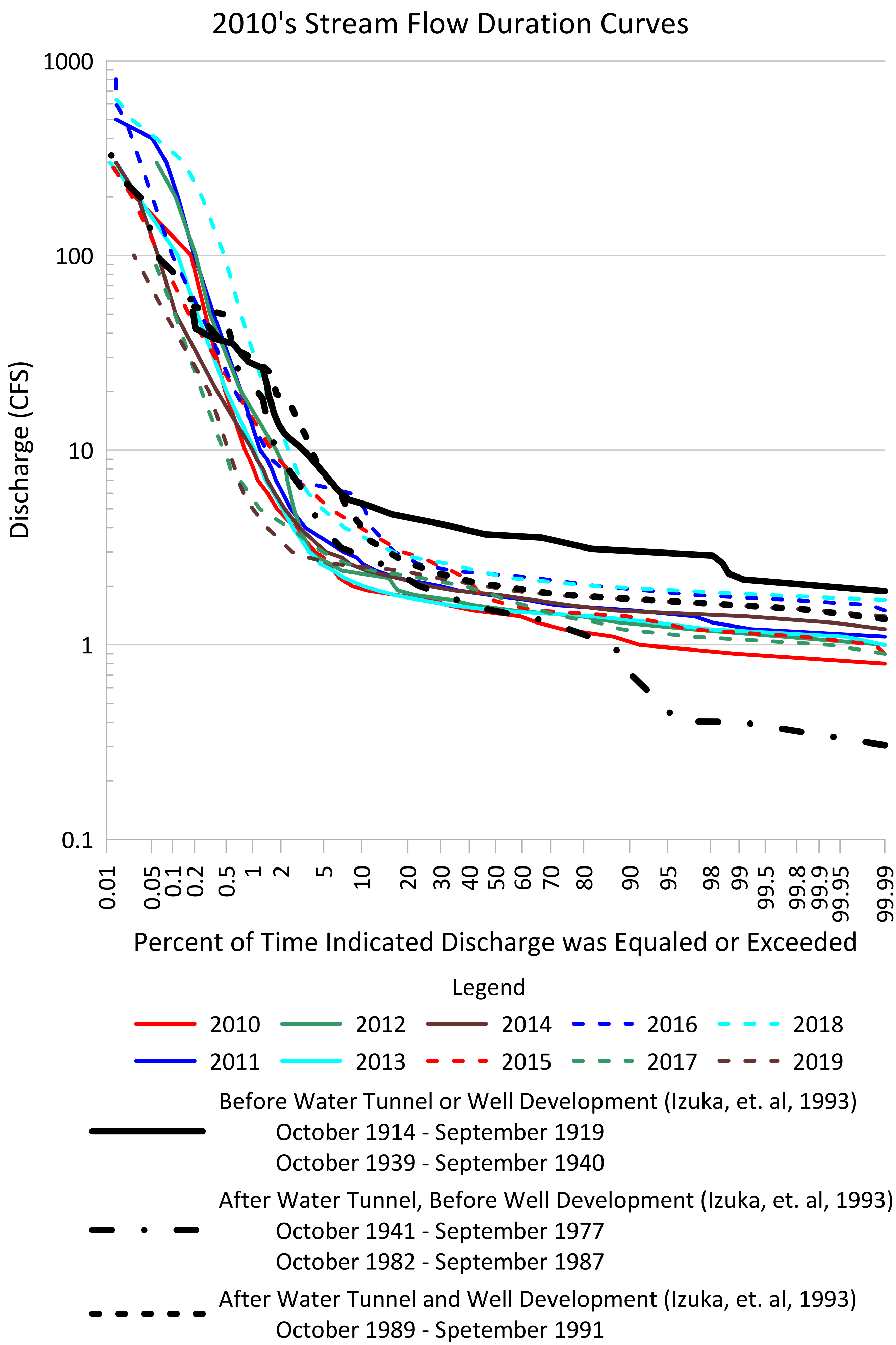

1970's Stream Flow Duration Curves
1000
100
10
1
0.1
Discharge (CFS)
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.5
99.8
99.9
99.95
99.99
Percent of Time Indicated Discharge was Equaled or Exceeded
Legend
1970
1972
1974
1976
1971
1973
1975
1977
Before Water Tunnel or Well Development (Izuka, et. al, 1993)
October 1914 - September 1919
October 1939 - September 1940
After Water Tunnel, Before Well Development (Izuka, et. al, 1993)
October 1941 - September 1977
October 1982 - September 1987
After Water Tunnel and Well Development (Izuka, et. al, 1993)
October 1989 - Spetember 1991


1980's Stream Flow Duration Curves
1000
100
10
1
0.1
Discharge (CFS)
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.5
99.8
99.9
99.95
99.99
Percent of Time Indicated Discharge was Equaled or Exceeded
Legend
1983
1985
1987
1989
1984
1986
1988
Before Water Tunnel or Well Development (Izuka, et. al, 1993)
October 1914 - September 1919
October 1939 - September 1940
After Water Tunnel, Before Well Development (Izuka, et. al, 1993)
October 1941 - September 1977
October 1982 - September 1987
After Water Tunnel and Well Development (Izuka, et. al, 1993)
October 1989 - Spetember 1991

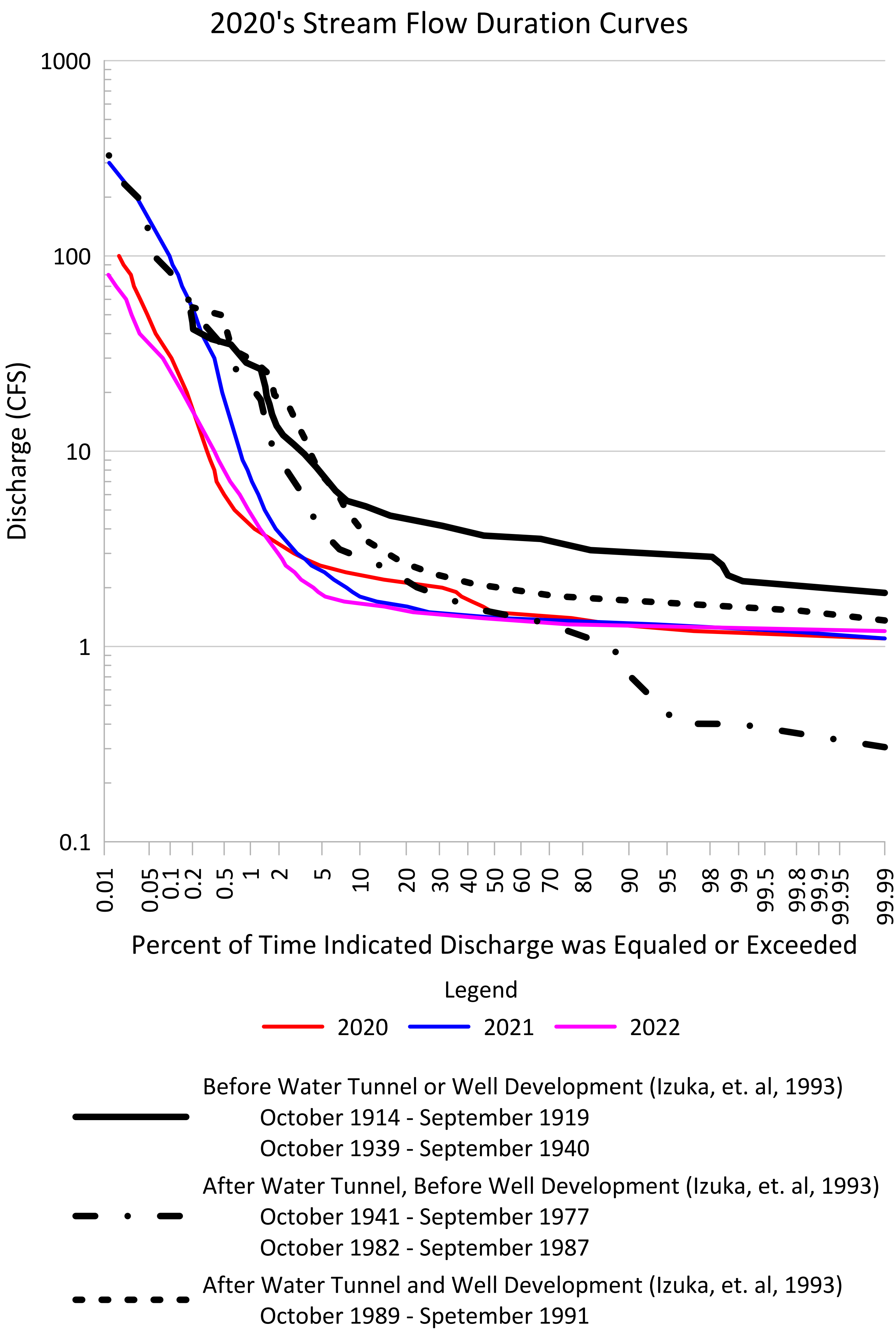

1990's Stream Flow Duration Curves
Discharge (CFS)
1000
100
10
1
0.1
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.5
99.8
99.9
99.95
99.99
Percent of Time Indicated Discharge was Equaled or Exceeded
Legend
1990
1992
1994
1996
1998
1991
1993
1995
1997
1999
Before Water Tunnel or Well Development (Izuka, et. al, 1993)
October 1914 - September 1919
October 1939 - September 1940
After Water Tunnel, Before Well Development (Izuka, et. al, 1993)
October 1941 - September 1977
October 1982 - September 1987
After Water Tunnel and Well Development (Izuka, et. al, 1993)
October 1989 - Spetember 1991



2000's Stream Flow Duration Curves
Discharge (CFS)
1000
100
10
1
0.1
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.5
99.8
99.9
99.95
99.99
Percent of Time Indicated Discharge was Equaled or Exceeded
Legend
2000
2002
2004
2006
2008
2001
2003
2005
2007
2009
Before Water Tunnel or Well Development (Izuka, et. al, 1993)
October 1914 - September 1919
October 1939 - September 1940
After Water Tunnel, Before Well Development (Izuka, et. al, 1993)
October 1941 - September 1977
October 1982 - September 1987
After Water Tunnel and Well Development (Izuka, et. al, 1993)
October 1989 - Spetember 1991

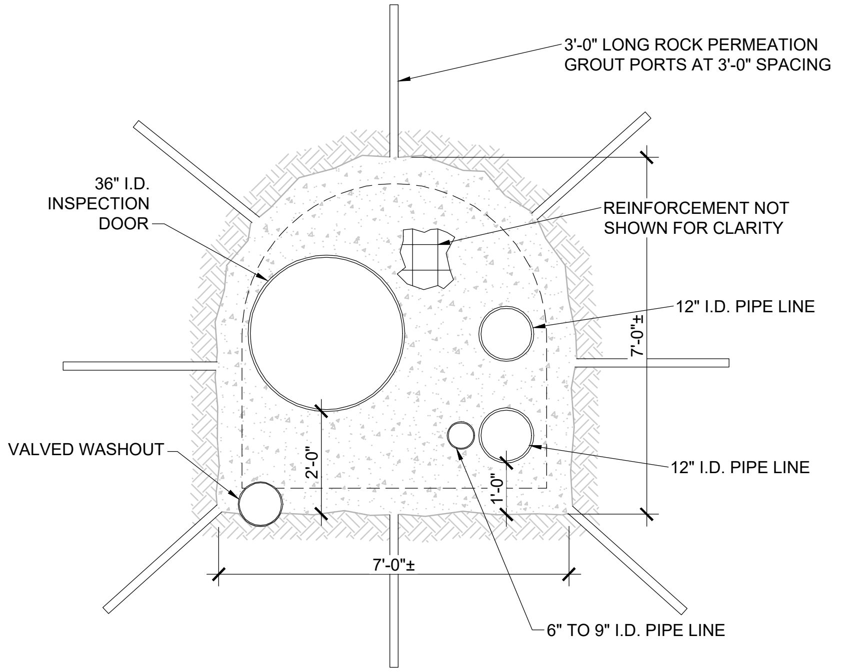


2010's Stream Flow Duration Curves
Discharge (CFS)
1000
100
10
1
0.1
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.5
99.8
99.9
99.95
99.99
Percent of Time Indicated Discharge was Equaled or Exceeded
Legend
2010
2012
2014
2016
2018
2011
2013
2015
2017
2019
Before Water Tunnel or Well Development (Izuka, et. al, 1993)
October 1914 - September 1919
October 1939 - September 1940
After Water Tunnel, Before Well Development (Izuka, et. al, 1993)
October 1941 - September 1977
October 1982 - September 1987
After Water Tunnel and Well Development (Izuka, et. al, 1993)
October 1989 - Spetember 1991

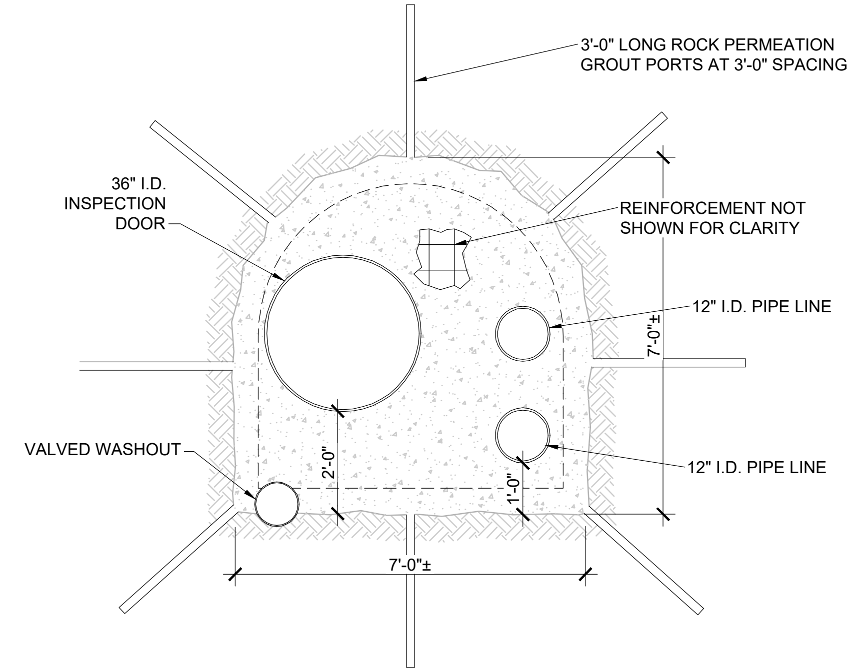

2020's Stream Flow Duration Curves
1000
100
10
1
0.1
Discharge (CFS)
0.01
0.05
0.1
0.2
0.5
1
2
5
10
20
30
40
50
60
70
80
90
95
98
99
99.5
99.8
99.9
99.95
99.99
Percent of Time Indicated Discharge was Equaled or Exceeded
Legend
2020
2021
2022
Before Water Tunnel or Well Development (Izuka, et. al, 1993)
October 1914 - September 1919
October 1939 - September 1940
After Water Tunnel, Before Well Development (Izuka, et. al, 1993)
October 1941 - September 1977
October 1982 - September 1987
After Water Tunnel and Well Development (Izuka, et. al, 1993)
October 1989 - Spetember 1991

APPENDIX C

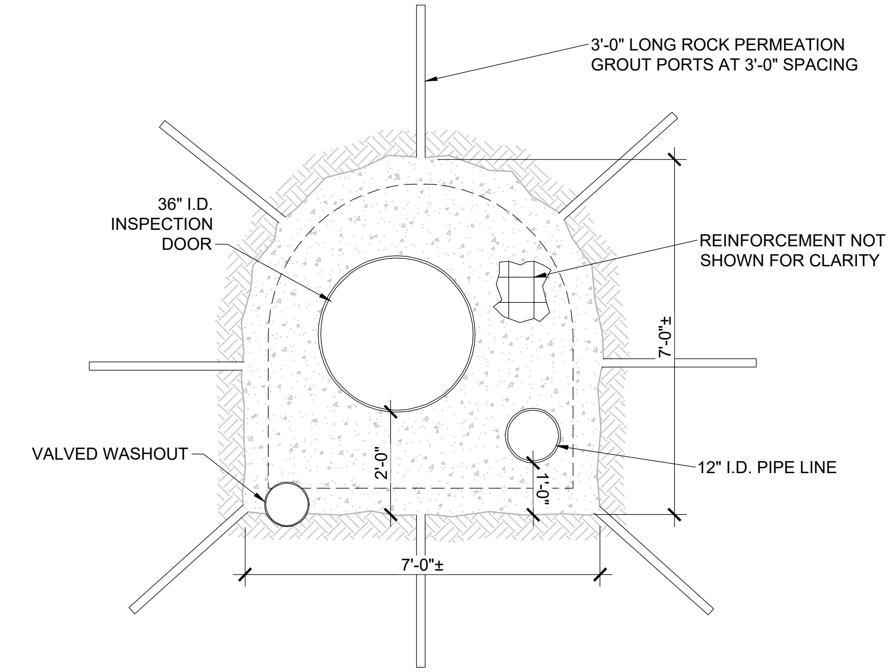
CONCEPTUAL BULKHEAD DESIGNS



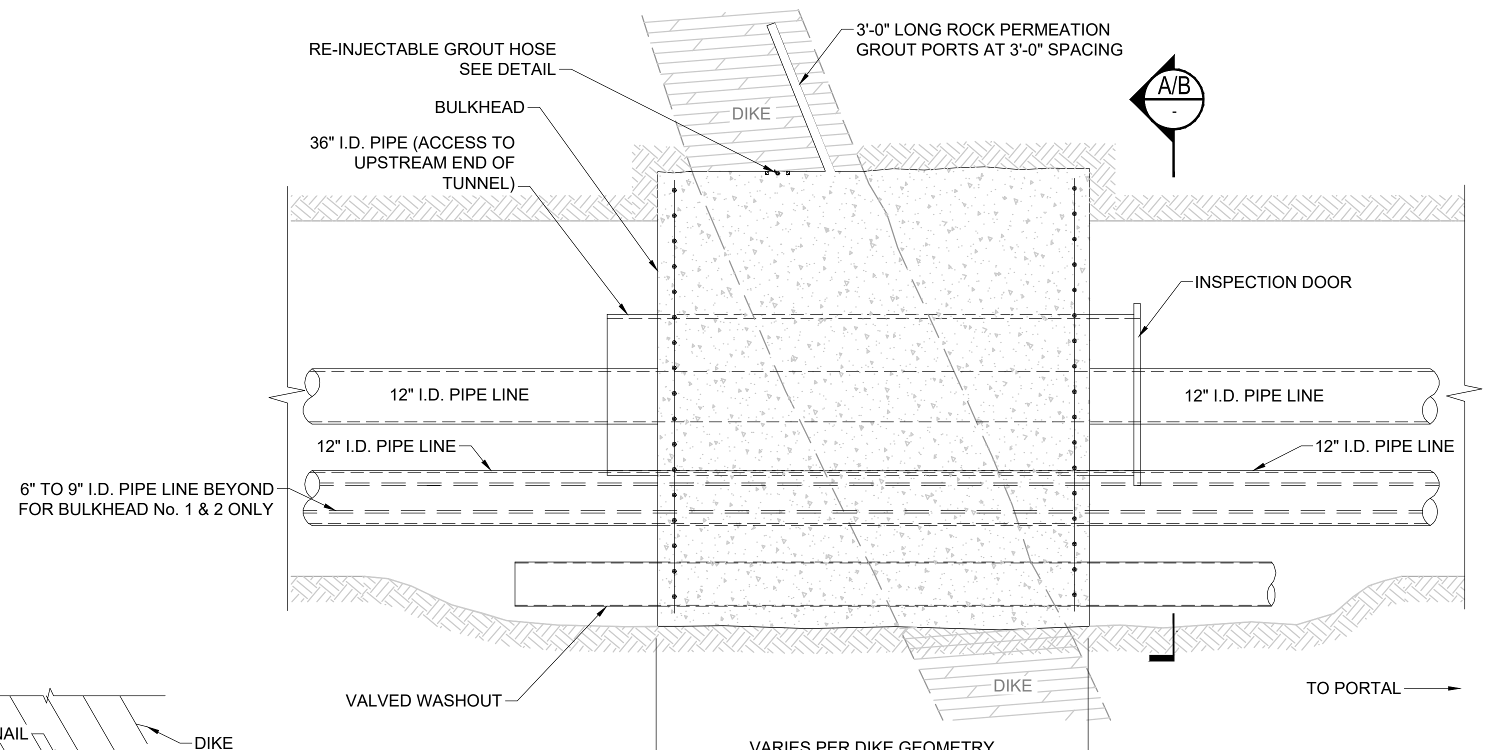
A / -- PROPOSED BULKHEAD No. 1 & 2 SECTION
SCALE: NTS



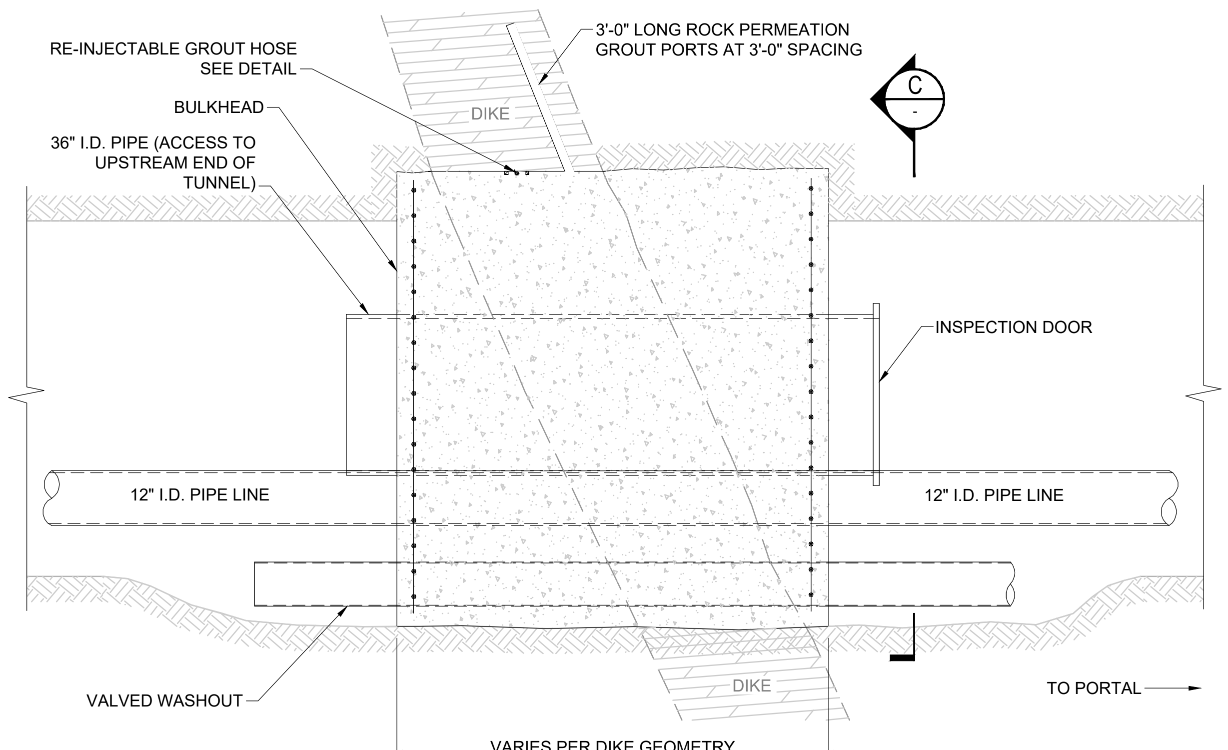
B / -- PROPOSED BULKHEAD No. 3 SECTION
SCALE: NTS



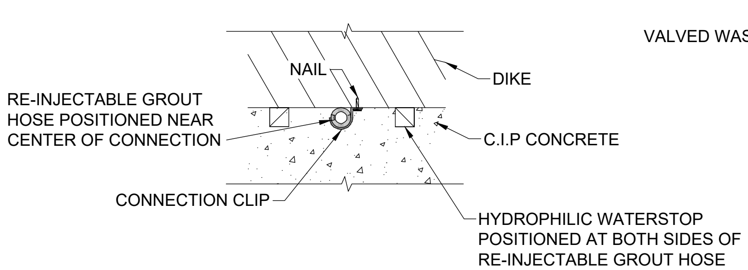
C / -- PROPOSED BULKHEAD No. 4 SECTION
SCALE: NTS



1 / -- PROPOSED BULKHEAD No. 1, 2, & 3 ELEVATION
SCALE: NTS



2 / -- PROPOSED BULKHEAD No. 4 ELEVATION
SCALE: NTS



D / -- RE-INJECTABLE GROUT HOSE DETAIL
SCALE: NTS

BRIERLEY ASSOCIATES
Creating Space Underground
500 ALA MOANA BLVD, SUITE 7400
HONOLULU, HI 96813
PH: 808.206.9036

CLIENT: HONOLULU BOARD OF WATER SUPPLY
630 S. BERETANIA ST.
HONOLULU, HI 96843

PROJECT NUMBER: HA'IKU TUNNEL BULKHEAD PRELIMINARY ENGINEERING STUDY

FIGURE/PLATE TITLE: PROPOSED BULKHEAD No. 1, 2, 3, & 4 DETAILS

FIGURE/PLATE: FIG.6

APPENDIX D

PLOTS OF RECHARGE ESTIMATES WITHIN THE HA’IKŪ VALLEY

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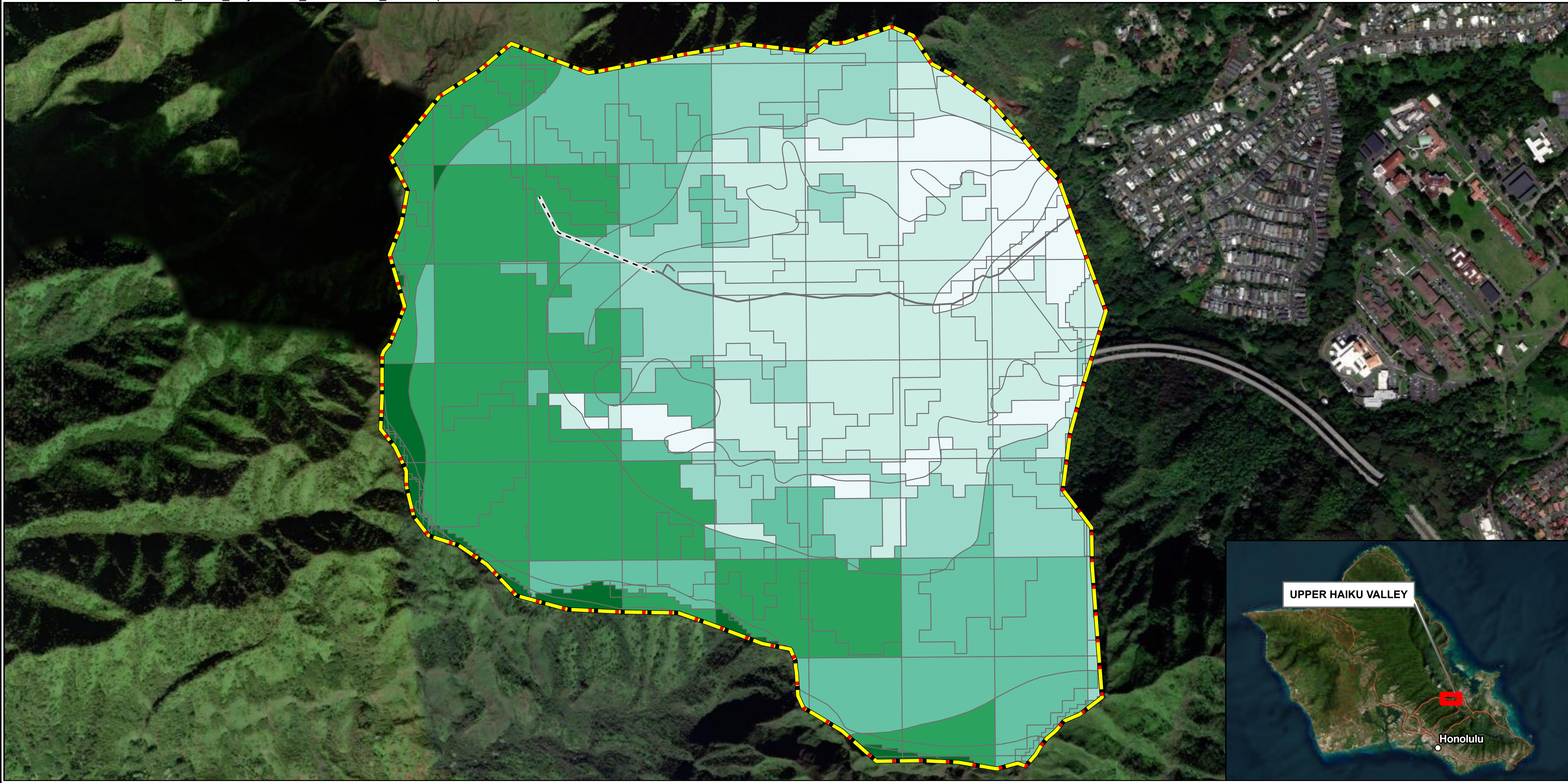


UPPER HAIKU VALLEY AOI

631.09 U.S. Survey Acres

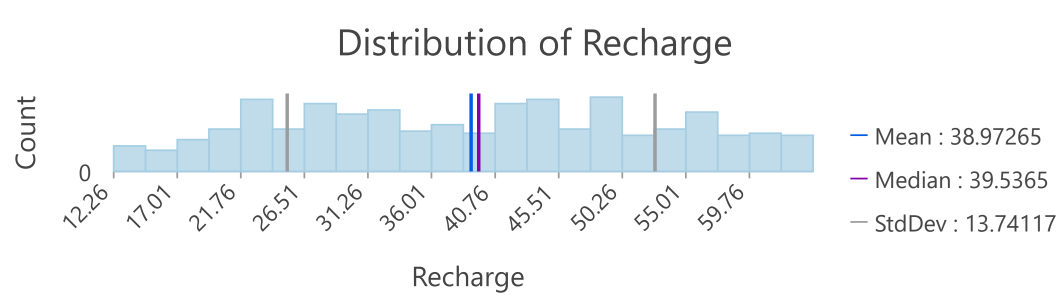
Tunnel Alignment

0 500 1,000 2,000 3,000 4,000 5,000 Feet

N

Average Recharge Rate 1978-2007 (Inches)

- 12.257000 - 21.343000
- 21.343001 - 29.430000
- 29.430001 - 37.761000
- 37.761001 - 46.017000
- 46.017001 - 53.937000
- 53.937001 - 64.514000



BRIERLEY ASSOCIATES
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HONOLULU, HI 96813
PH: 808.206.9036

CLIENT
HONOLULU BOARD OF WATER SUPPLY
630 S. BERETANIA ST.
HONOLULU, HI 96843

PROJECT NUMBER
HA'IKU TUNNEL BULKHEAD
PRELIMINARY ENGINEERING STUDY

FIGURE/PLATE TITLE
UPPER HA'IKU VALLEY
RECHARGE RATE

FIGURE/PLATE
FIG.7

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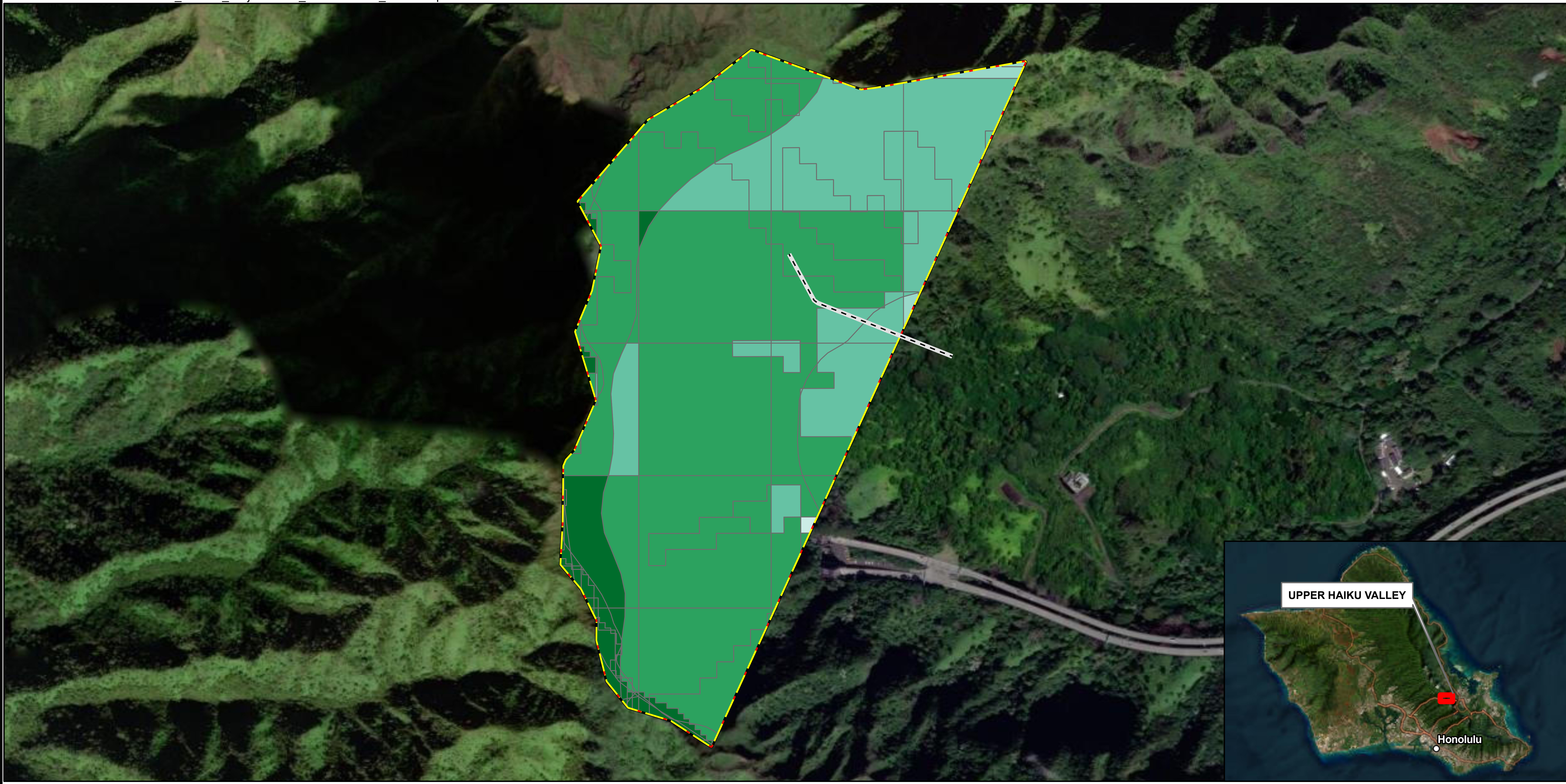


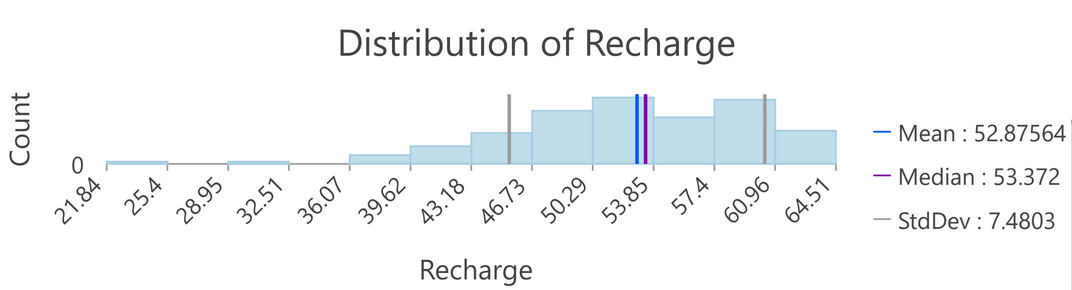
Average Recharge Rate 1978-2007 (Inches)
- 12.257000 - 21.343000
- 21.343001 - 29.430000
- 29.430001 - 37.761000
- 37.761001 - 46.017000
- 46.017001 - 53.937000
- 53.937001 - 64.514000

UPPER HAIKU VALLEY AOI
631.09 U.S. Survey Acres

Tunnel Alignment

0 500 1,000 2,000 3,000 4,000 5,000 Feet

N



BRIERLEY ASSOCIATES
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HONOLULU, HI 96813
PH: 808.206.9036

CLIENT
HONOLULU BOARD OF WATER SUPPLY
630 S. BERETANIA ST.
HONOLULU, HI 96843

PROJECT NUMBER
HA'IKU TUNNEL BULKHEAD
PRELIMINARY ENGINEERING STUDY

FIGURE/PLATE TITLE
UPPER HA'IKU VALLEY
TUNNEL COMPARTMENT
AVERAGE RECHARGE RATE

FIGURE/PLATE
FIG.8

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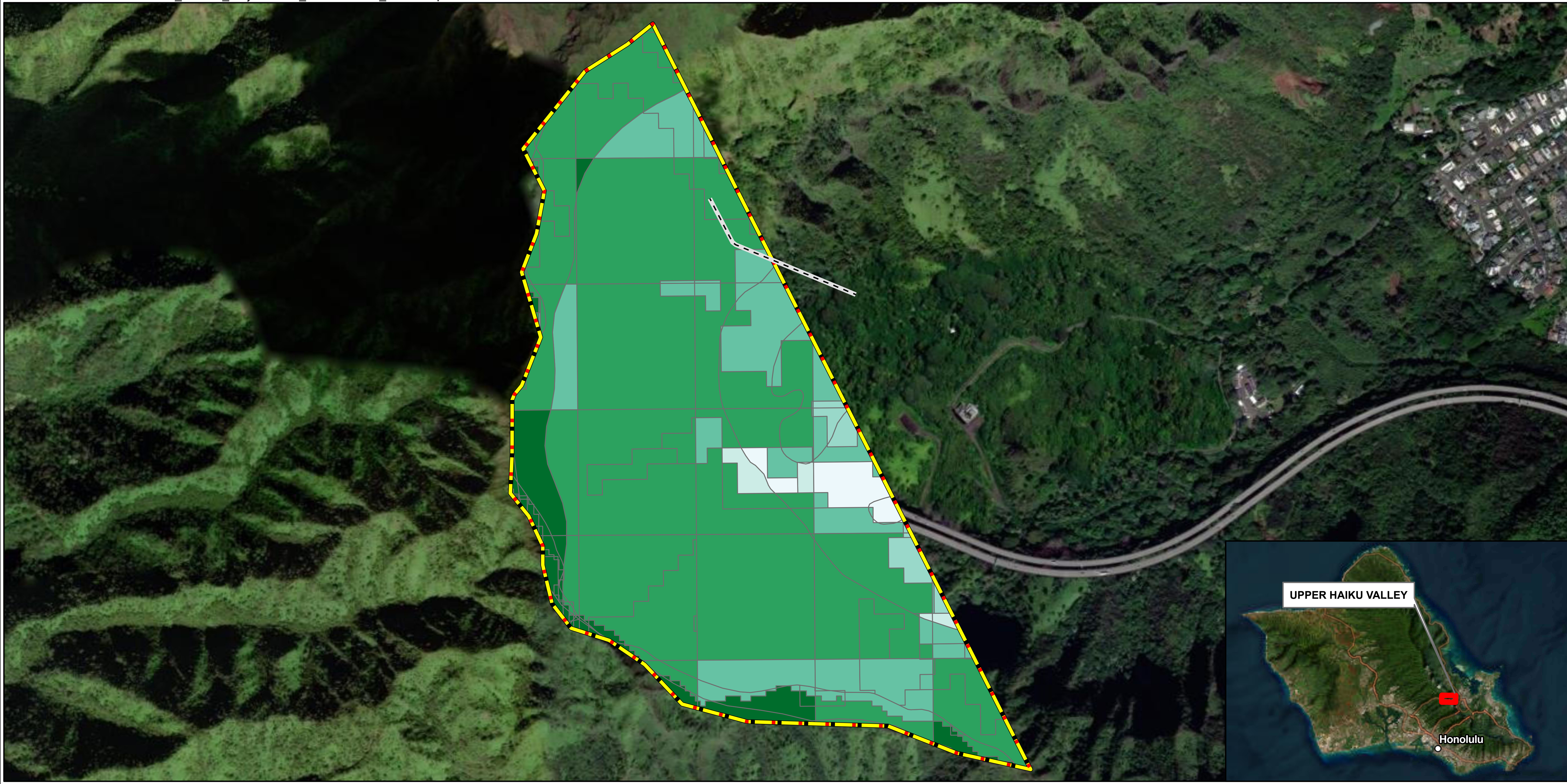


Tunnel Compartment 2

189.10 U.S. Survey Acres

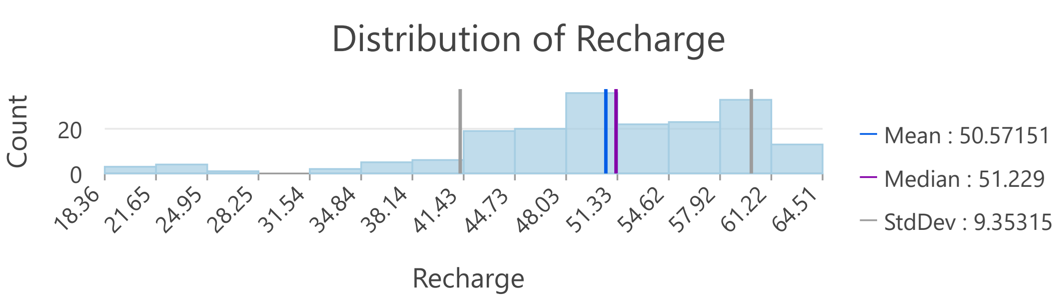
Tunnel Alignment

0 400 800 1,600 2,400 3,200 4,000 Feet

N

Average Recharge Rate 1978-2007 (Inches)

- 12.257000 - 21.343000
- 21.343001 - 29.430000
- 29.430001 - 37.761000
- 37.761001 - 46.017000
- 46.017001 - 53.937000
- 53.937001 - 64.514000



BRIERLEY ASSOCIATES
Creating Space Underground
500 ALA MOANA BLVD, SUITE 7400
HONOLULU, HI 96813
PH: 808.206.9036

CLIENT	FIGURE/PLATE TITLE	FIGURE/PLATE
HONOLULU BOARD OF WATER SUPPLY 630 S. BERETANIA ST. HONOLULU, HI 96843	UPPER HA'IKU VALLEY TUNNEL COMPARTMENT 2 AVERAGE RECHARGE RATE	FIG.9
PROJECT NUMBER HA'IKU TUNNEL BULKHEAD PRELIMINARY ENGINEERING STUDY		

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APPENDIX E

Engineer's Opinion of Probable Cost

Ha'ikū Tunnel

Alternative 3 Estimated Project Schedule

Task ID	Task Name	Estimated Time in Months																							
		January (Year 1)	February	March	April	May	June	July	August	September	October	November	December	January (Year 2)	February	March	April	May	June	July	August	September	October	November	December
1	Prepatory Submittals & Permits																								
2	Site Mobilization																								
3	Portal Access Improvements																								
4	Tunnel Safety & Access																								
5	Material Handling System																								
6	Demo Exs Piping & Bulkheads 1/2																								
7	Rebuild Piping & Bulkheads 1/2																								
8	Commission Rehabilitated Tunnel																								
9	Site Restoration & Demobilization																								

Ha'ikū Tunnel

BRIERLEY ASSOCIATES
Creating Space Underground

Engineer's Opinion of Probable Cost: Alternative 3

Estimate Summary

Activity Cost Summary

Item #	Schedule Activity		Activity Total
1	Permitting & Submittals		$95,000
2	Site Mobilization		$577,000
3	Portal Access Improvements		$405,500
4	Tunnel Safety & Access		$430,000
5	Material Handling System Installation		$352,500
6	Demolish Existing Piping & Bulkheads #1 & #2		$575,000
7	Rebuild Piping & Bulkheads #1 & #2		$1,402,500
8	Commission Rehabilitated Tunnel		$239,000
9	Site Restoration & Demobilization		$197,000
10	Reserved		$0
11	Reserved		$0
12	Reserved		$0
		Activity Subtotal	**$4,273,500**

Indirect Costs

Item		Indirect Total
Unallocated Indirects		$0
Field Overhead (Indirect costs)		$1,106,441
Home Office Overhead (3% of direct costs)		$128,205
Bonding & Insurance (2% of direct costs)		$85,470
	Indirect Subtotal	**$1,320,116**

Total Contractor Cost

Activity Cost + Indirect Costs	**Total Contractor Cost**	**$5,593,616**

Profit

Profit (30%)	$1,678,085
Total Cost with Profit	**$7,271,700**

Engineer's Opinion of Probable Cost Range

High End of High Range (+50%)	**$10,907,550**
Low End of Low Range (-30%)	**$5,090,190**

Ha'ikū Tunnel

BRIERLEY ASSOCIATES
Creating Space Underground

Engineer's Opinion of Probable Cost: Alternative 3

Activity Cost Items

Item #	1	Permitting & Submittals

Quantity	Activity Sub Item		Sub Item Cost
1 LS	Permitting Fees		$25,000
1 LS	Outside Engineering		$50,000
1 LS	Industrial Hygenist Planning		$20,000
		Item Subtotal	**$95,000**

Item #	2	Site Mobilization

Quantity	Activity Sub Item		Sub Item Cost
8	Crew Labor Weeks		$214,000
8	Crew Tools & Supplies		$64,000
4	Industrial Hygenist On-site Weeks		$16,000
4	Support Equipment		$8,000
1	Fencing/Barricades/Signage		$25,000
1	Decontamination Facility (Furnish)		$100,000
1	Ventilation Equipment (Furnish)		$150,000
		Item Subtotal	**$577,000**

Item #	3	Portal Access Improvements

Quantity	Activity Sub Item		Sub Item Cost
6	Crew Labor Weeks		$160,500
6	Crew Tools & Supplies		$48,000
6	Support Equipment		$12,000
2500	Gravel (CY)		$125,000
20000	Lumber (BF)		$60,000
		Item Subtotal	**$405,500**

Ha'ikū Tunnel

BRIERLEY ASSOCIATES
Creating Space Underground

Engineer's Opinion of Probable Cost: Alternative 3

Item #	4	Tunnel Safety & Access

Quantity	Activity Sub Item	Sub Item Cost
8	Crew Labor Weeks	$214,000
8	Crew Tools & Supplies	$64,000
4	Industrial Hygenist On-site Weeks	$16,000
8	Support Equipment	$16,000
120	Rock Bolts (ea.)	$120,000
	Item Subtotal	**$430,000**

Item #	5	Material Handling System Installation

Quantity	Activity Sub Item	Sub Item Cost
6	Crew Labor Weeks	$160,500
6	Crew Tools & Supplies	$48,000
3	Industrial Hygenist On-site Weeks	$12,000
6	Support Equipment	$12,000
1 LS	Tunnel Access System - Materials	$120,000
	Item Subtotal	**$352,500**

Item #	6	Demolish Existing Piping & Bulkheads #1 & #2

Quantity	Activity Sub Item	Sub Item Cost
12	Crew Labor Weeks	$321,000
12	Crew Tools & Supplies	$96,000
6	Industrial Hygenist On-site Weeks	$24,000
12	Demolition & Support Equipment	$84,000
1 LS	Haul off & dispose/recycle waste materials	$50,000
	Item Subtotal	**$575,000**

Ha'ikū Tunnel

BRIERLEY ASSOCIATES
Creating Space Underground

Engineer's Opinion of Probable Cost: Alternative 3

Item #	7	Rebuild Piping & Bulkheads #1 & #2

Quantity	Activity Sub Item	Sub Item Cost
16	Crew Labor Weeks	$428,000
16	Crew Tools & Supplies	$128,000
8	Industrial Hygenist On-site Weeks	$32,000
16	Support Equipment	$32,000
40	CY Concrete	$40,000
10000	LB Reinforcing Steel	$20,000
2	Bulkhead Grouting	$40,000
2500	Lumber (BF)	$7,500
1800	LF 12in Ductile Iron Pipe	$225,000
1	DIP Valves, Fittings, Controls	$200,000
1	Tunnel Instrumentation & Controls	$250,000
	Item Subtotal	**$1,402,500**

Item #	8	Commission Rehabilitated Tunnel

Quantity	Activity Sub Item	Sub Item Cost
4	Crew Labor Weeks	$107,000
2	Crew Tools & Supplies	$16,000
2	Industrial Hygenist On-site Weeks	$8,000
4	Support Equipment	$8,000
1	Commissioning Chemicals & Supplies	$100,000
	Item Subtotal	**$239,000**

Item #	9	Site Restoration & Demobilization

Quantity	Activity Sub Item	Sub Item Cost
4	Crew Labor Weeks	$107,000
4	Crew Tools & Supplies	$32,000
0	Industrial Hygenist On-site Weeks	$0
4	Support Equipment	$8,000
1 LS	Haul off & dispose/recycle waste materials	$50,000
	Item Subtotal	**$197,000**

Ha'ikū Tunnel

BRIERLEY ASSOCIATES
Creating Space Underground

Engineer's Opinion of Probable Cost: Alternative 3

Item #	Indirect	Indirect Costs

Quantity	Activity Sub Item		Sub Item Cost
21	Project Manager (MO)		$454,965
21	Field Engineer (MO)		$318,476
18	Field Office (MO)		$90,000
42	Pickup Truck - operated (MO)		$63,000
18	Ventilation Equipment O & M (MO)		$180,000
		Item Subtotal	**$1,106,441**

Ha'ikū Tunnel

Engineer's Opinion of Probable Cost: Alternative 2

Estimate Summary

Activity Cost Summary

Item #	Schedule Activity		Activity Total
1	Permitting & Submittals		$95,000
2	Site Mobilization		$577,000
3	Portal Access Improvements		$405,500
4	Tunnel Safety & Access		$430,000
5	Material Handling System Installation		$352,500
6	Demolish Existing Piping & Bulkheads No. 1, 2, and 3		$945,000
7	Build Piping & Bulkheads No. 1, 2, 3, 4		$1,903,250
8	Commission Rehabilitated Tunnel		$239,000
9	Site Restoration & Demobilization		$197,000
10	Reserved		$0
11	Reserved		$0
12	Reserved		$0
		Activity Subtotal	**$5,144,250**

Indirect Costs

Item		Indirect Total
Unallocated Indirects		$0
Field Overhead (Indirect costs)		$1,255,932
Home Office Overhead (3% of direct costs)		$154,328
Bonding & Insurance (2% of direct costs)		$102,885
	Indirect Subtotal	**$1,513,145**

Total Contractor Cost

Activity Cost + Indirect Costs	**Total Contractor Cost**	**$6,657,395**

Profit

Profit (30%)	$1,997,218
Total Cost with Profit	**$8,654,613**

Engineer's Opinion of Probable Cost Range

High End of High Range (+50%)	**$12,981,919**
Low End of Low Range (-30%)	**$6,058,229**

Ha'ikū Tunnel

Engineer's Opinion of Probable Cost: Alternative 2

BRIERLEY ASSOCIATES
Creating Space Underground

Activity Cost Items

Item # 1 — Permitting & Submittals

Quantity	Activity Sub Item		Sub Item Cost
1 LS	Permitting Fees		$25,000
1 LS	Outside Engineering		$50,000
1 LS	Industrial Hygenist Planning		$20,000
		Item Subtotal	**$95,000**

Item # 2 — Site Mobilization

Quantity	Activity Sub Item		Sub Item Cost
8	Crew Labor Weeks		$214,000
8	Crew Tools & Supplies		$64,000
4	Industrial Hygenist On-site Weeks		$16,000
4	Support Equipment		$8,000
1	Fencing/Barricades/Signage		$25,000
1	Decontamination Facility (Furnish)		$100,000
1	Ventilation Equipment (Furnish)		$150,000
		Item Subtotal	**$577,000**

Item # 3 — Portal Access Improvements

Quantity	Activity Sub Item		Sub Item Cost
6	Crew Labor Weeks		$160,500
6	Crew Tools & Supplies		$48,000
6	Support Equipment		$12,000
2500	Gravel (CY)		$125,000
20000	Lumber (BF)		$60,000
		Item Subtotal	**$405,500**

Ha'ikū Tunnel

Engineer's Opinion of Probable Cost: Alternative 2

BRIERLEY ASSOCIATES
Creating Space Underground

Item #	4	Tunnel Safety & Access

Quantity	Activity Sub Item		Sub Item Cost
8	Crew Labor Weeks		$214,000
8	Crew Tools & Supplies		$64,000
4	Industrial Hygenist On-site Weeks		$16,000
8	Support Equipment		$16,000
120	Rock Bolts (ea.)		$120,000
		Item Subtotal	**$430,000**

Item #	5	Material Handling System Installation

Quantity	Activity Sub Item		Sub Item Cost
6	Crew Labor Weeks		$160,500
6	Crew Tools & Supplies		$48,000
3	Industrial Hygenist On-site Weeks		$12,000
6	Support Equipment		$12,000
1 LS	Tunnel Access System - Materials		$120,000
		Item Subtotal	**$352,500**

Item #	6	Demolish Existing Piping & Bulkheads No. 1, 2, and 3

Quantity	Activity Sub Item		Sub Item Cost
20	Crew Labor Weeks		$535,000
20	Crew Tools & Supplies		$160,000
10	Industrial Hygenist On-site Weeks		$40,000
20	Demolition & Support Equipment		$140,000
1 LS	Haul off & dispose/recycle waste materials		$70,000
		Item Subtotal	**$945,000**

Ha'ikū Tunnel

Engineer's Opinion of Probable Cost: Alternative 2

Item #	7	Build Piping & Bulkheads No. 1, 2, 3, 4

Quantity	Activity Sub Item	Sub Item Cost
27	Crew Labor Weeks	$722,250
27	Crew Tools & Supplies	$216,000
14	Industrial Hygenist On-site Weeks	$56,000
27	Support Equipment	$54,000
65	CY Concrete	$65,000
15000	LB Reinforcing Steel	$30,000
4	Bulkhead Grouting	$40,000
3750	Lumber (BF)	$11,250
1950	LF 12in Ductile Iron Pipe	$243,750
1	DIP Valves, Fittings, Controls	$215,000
1	Tunnel Instrumentation & Controls	$250,000
	Item Subtotal	**$1,903,250**

Item #	8	Commission Rehabilitated Tunnel

Quantity	Activity Sub Item	Sub Item Cost
4	Crew Labor Weeks	$107,000
2	Crew Tools & Supplies	$16,000
2	Industrial Hygenist On-site Weeks	$8,000
4	Support Equipment	$8,000
1	Commissioning Chemicals & Supplies	$100,000
	Item Subtotal	**$239,000**

Item #	9	Site Restoration & Demobilization

Quantity	Activity Sub Item	Sub Item Cost
4	Crew Labor Weeks	$107,000
4	Crew Tools & Supplies	$32,000
0	Industrial Hygenist On-site Weeks	$0
4	Support Equipment	$8,000
1 LS	Haul off & dispose/recycle waste materials	$50,000
	Item Subtotal	**$197,000**

Ha'ikū Tunnel

Engineer's Opinion of Probable Cost: Alternative 2

BRIERLEY ASSOCIATES
Creating Space Underground

Item #	Indirect	Indirect Costs

Quantity	Activity Sub Item		Sub Item Cost
24	Project Manager (MO)		$519,960
24	Field Engineer (MO)		$363,972
20	Field Office (MO)		$100,000
48	Pickup Truck - operated (MO)		$72,000
20	Ventilation Equipment O & M (MO)		$200,000
		Item Subtotal	**$1,255,932**

Ha'ikū Tunnel

Engineer's Opinion of Probable Cost: Alternative 4

BRIERLEY ASSOCIATES
Creating Space Underground

Estimate Summary

Activity Cost Summary

Item #	Schedule Activity		Activity Total
1	Permitting & Submittals		$150,000
2	Site Mobilization		$750,000
3	Portal Access Improvements		$125,000
4	Tunnel Safety & Access		$750,000
5	Excavation of Tunnel No. 2		$11,000,000
6	Install & grout carrier piping		$3,300,000
7	Commission New Tunnel		$400,000
8	Decommission Existing Haiku Tunnel		$500,000
9	Site Restoration & Demobilization		$250,000
10			$0
11			$0
12			$0
		Activity Subtotal	**$17,225,000**

Indirect Costs

Item		Indirect Total
Unallocated Indirects		$0
Field Overhead (Indirect costs)		$1,883,898
Home Office Overhead (3% of direct costs)		$516,750
Bonding & Insurance (2% of direct costs)		$344,500
	Indirect Subtotal	**$2,745,148**

Total Contractor Cost

Activity Cost + Indirect Costs	**Total Contractor Cost**	**$19,970,148**

Profit

Profit (30%)	$5,991,044
Total Cost with Profit	**$25,961,192**

Engineer's Opinion of Probable Cost Range

High End of High Range (+100%)	**$51,922,385**
Low End of Low Range (-50%)	**$12,980,596**

APPENDIX F

"HAIKU TUNNEL STUDY" BY S.P. BOWLES
BOARD OF WATER SUPPLY
1969

HAIKU TUNNEL STUDY

by S. P. Bowles

Hydrology & Geology Section
Planning, Resources & Research Division
Board of Water Supply
1969

Recent studies by the U. S. Geological Survey (Hirashima 1963, Takasaki, et al, 1969) have estimated a storage potential in the Haiku Tunnel dike compartments of about 1.4 billion gallons. Board of Water Supply estimates are closer to 2 billion gallons at 95 psi. Regardless of the number used, a large potential storage unit is tapped by the tunnel and the present locations of the bulkheads are such that pressures greater than 20 to 25 psi cannot be realized without significant wastage to Haiku stream.

The research committee of the BWS, recognizing the significance of potential storage, outlined a study to determine the feasibility of placing a fourth bulkhead farther back in the tunnel so that the storage might be fully utilized in a manner similar to the operations of Waihee tunnel. In April of 1969, Haiku tunnel was opened and systematic flow measurements and detailed geologic studies were made. Following the investigations, the tunnel was restored to its normal operating condition and, after a period of complete shut in, the tunnel was returned to service.

Construction of Haiku tunnel began in 1940 under the direction of C. K. Wentworth, geologist for the Honolulu Board of Water Supply. The purpose of the tunnel was to supply water, under the auspices of the Suburban Water System, to the Kaneohe-Kailua area. In 1938, Wentworth and the U. S. Geological Survey had measured gains in Haiku stream up to an elevation of 682 feet (Table 1). Above this point the stream was dry. It was decided that a water tunnel at the 550 foot elevation would recover the emerging water and also tap any dike compartments which might be in the path of the tunnel. There are no visible dikes on the surface above the tunnel alignment. On the basis of the gain in Haiku stream discharge, Wentworth concluded that dikes were the controlling geologic structure and the stream flow represented spill from underlying compartments. Figure 1 illustrates the surface profile, crossection of the tunnel and significant dikes.

Tunnel direction, adits, and distances as determined during the recent opening of the tunnel are presented in Figure 2. During the period of construction, frequent oriface points were evident in the tunnel face. The changes in tunnel direction and the several adits indicate that efforts were made to follow these "veins" of water. The first water was struck at 600 feet, which is the location of bulkhead #2 (Figure 3). A thin dike was penetrated and about 3 mgd (million gallons daily) was developed. When the bore reached 700 feet, flow had dropped to about 1.5 mgd. The tunnel intersected a second thin dike several times until a distance of 900 feet was reached where bulkhead #3 was constructed (Figure 4). At 860 feet, the tunnel direction changed 42 degrees in a northerly direction. A short adit at 900 feet penetrates a dike 1.5 feet thick. The main tunnel was continued to a distance of 980 feet with the flow remaining at 1.5 mgd. At 980 feet, the tunnel cut a dike 3.5 feet thick, after which the flow increased steadily to 6 mgd at 1178 feet from the portal. A dike was originally reported at this point, however the recent study found a dense aa flow crossing the tunnel at a slight dip. From 1178 feet to the termination of the tunnel at 1200 feet, the flow jumped to a peak of 11.3 mgd. The last 20 feet of tunnel is cut in clinker. Apparently the sudden contrast in permeability and rapid increase in flow gave the impression that a dike compartment had been tapped.

Following the construction of bulkheads, concrete lining and piping, the tunnel was shut in and a pressure of from 90 to 95 psi was recorded. The tunnel was then opened and a flush flow of 11.9 mgd was measured. After detecting leakage around bulkhead #1, a pipe was placed through bulkhead #2 and sealed. It was found that at pressures of 20 to 25 psi, Haiku Stream would begin to flow in a manner similar to that recorded by the U. S. Geological Survey in 1938 (Table 1). Because of the leakage at these pressures, Haiku Tunnel has been permitted to free flow at an average annual rate of about 2 mgd. Whenever demand decreases and the pressure reaches about 20 psi, the stream flows and significant amounts of water are wasted to sea.

Recent flow measurements made by personnel of the Hydrology and Geology Section are summarized in Table 2. About 55 per cent of the discharge originates in the last fifty feet of tunnel through numerous orifaces scattered around the tunnel bore (Plate 1). At station 9 + 50 the flow was about 97 per cent of the total tunnel discharge at the time of the investigation. Behind the dike at 9 + 80, the country rock was completely saturated (Plate 2). Such a condition was not anticipated because it was felt that once the tunnel had been reduced to its base flow, the rock would be unsaturated to the level of the tunnel stream. After the many years of operation under free flow it was thought that the storage had been completely removed. As noted in Table 2, a measurement was made at the tunnel heading showing a pressure of 23 psi or about 53 feet of water. This pressure, when compared with the original of 90 to 95 psi, shows a significant amount of storage is extremely slow in draining from the compartment. The most reasonable explanation for this characteristic

PLATE 1

VIEW OF HAIKU TUNNEL HEADING. MAJORITY OF DISCHARGE IS FROM DRILL HOLES IN CLINKER.

P L A T E 2

VIEW LOOKING TOWARDS PORTAL AT ABOUT 1000 FEET IN HAIKU TUNNEL SHOWING SATURATED ROCK IN FOREGROUND AND DIKE AT STATION 9 + 80.

is that the tunnel did not penetrate far enough into the highly permeable clinker at the tunnel terminus. While all of the dike compartment, beginning at 9 + 80 feet, is saturated, the pahoehoe lavas have a contrastingly lower permeability in the first two hundred feet behind the dike. In order to obtain the optimum storage and flow potential of the tunnel, the hydraulic characteristics of the tunnel bore must be altered to permit rapid dewatering. While the geometry of the dike compartment is not known, a large amount of the storage potential is unused.

After completing investigation within the tunnel, bulkhead #1 was closed and the tunnel was permitted to fill at about 2.4 mgd. It was felt that the concrete lining between bulkhead #1 and bulkhead #2 would be sufficiently water tight to retain the water normally held at bulkhead #2. After closing the valve on the 8 inch wash out line and the 16 inch main, the tunnel was permitted to fill. At about 10 psi, water was pouring out of the portal. It appeared that between 1 and 2 mgd was escaping through the concrete lining. The valves were reopened and necessary piping reinstalled for closing bulkhead #2.

On May 2 the valves were again closed and allowed to recover. Figure 5 is a plot of the tunnel recovery starting May 2. Leakage to Haiku stream was well established at a tunnel pressure of 25 psi or 58 feet of water.

Takasaki, et al, (1969) developed an emperical equation for determining recession constants for all of the major tunnels penetrating dike compartments in the Koolau Range. When simplified the equation becomes

$$Q_t = bS + Q_o$$

where Q_o = lower discharge at initial time;

Q_t = higher discharge at the end of time;

t = time, in days;

S = storage in gallons;

b = equivalent to recession constant.

The equation shows a linear relationship between discharge and storage. For Haiku tunnel, Hirashima (1963) concluded that total storage from 90 psi to 0 psi, as measured at the tunnel discharge line, was 1.4 billion gallons. The recession constant from Takasaki for Haiku is shown as 0.00436. Because the recent study found that the aquifer pressure is 23 psi at a lower Q of 2.4 mgd rather than 0 psi at 2 mgd, questions are raised as to the validity of the recession constant given by Takasaki. Assuming that the recession constant is valid, further, that the measured pressure is directly proportional to storage, ie, 23 psi is equivalent one fourth of the original storage of 1.4 billion gallons at 90 psi, then solution of the equation should give a discharge equivalent to that measured during the investigation (2.4 mgd). Solving the equation, the discharge indicated is actually 3.7 mgd, suggesting that the use of discharge line pressure is not a sound measure of aquifer pressure and is adversely influenced by drawdown effects in the tunnel. It is unlikely that the remaining storage was ever useable, however it can be recovered by decreasing the drawdown effects in the tunnel either by extending the tunnel or by drilling a series of horizontal holes at or near the heading.

Mink (1962) developed a series management criteria for Waihee tunnel setting forth operational techniques so that the tunnel storage of about 2.2 billion gallons might be used to its fullest potential.

Mink (1967), after extensive modification of his original theoretical equations, later concluded that the original emperical approach by Takasaki, et al, provided the most sound method of evaluating the free flow-storage relationship. Before proper management practices can be established for Haiku tunnel, several changes in its construction must be made.

The operational experience at Waihee tunnel over a period of ten years has indicated the value of ground water stored within dike compartments. Without such storage available, the Windward system could not have met the tremendous increase in demand during that period. Furthermore, the systematic depletion of storage at Waihee tunnel allowed the development of the Punaluu well field and construction of the 30-inch transmission main from Punaluu to Kaneohe. Had storage not been available, numerous small sources would have been needed to meet demand requirements, as the construction time for the Punaluu system was considerable.

With Punaluu water presently available, Waihee tunnel flow will be in excess of demand until the transmission link is made from Waimanalo to Hawaii Kai. Haiku tunnel, while it can be providing high service water by gravity, may be kept off the line for several years so that rehabilitation of the tunnel can take place. The following steps are recommended for the systematic reconstruction of the tunnel:

1. Remove existing bulkheads.
2. Extend the heading of the tunnel 100 feet or drill about six 3 inch diameter holes horizontally from the present heading.
3. Construct a bulkhead in the dike at station 9 + 80 as shown

in Figure 6. Install an adequate system of pressure lines behind the new bulkhead.

4. Shut in the new bulkhead and permit the storage to rebuild. The long term recharge rate is about 2 mgd (Hirashima 1963). Using Hirashima's storage estimate of 1.4 billion gallons, about two years will be required to recover the original storage. It is likely that the recovery time will be less if it occurs during wet years as the recharge rate will be greater than 2 mgd.

5. During the recovery stage, the new bulkhead can be fully opened periodically to obtain free flow-pressure relationships. This will provide data for the development of operational techniques for utilizing both short and long term releases from storage.

6. After adequate knowledge of operational techniques has been obtained, a pipeline can be designed and constructed leading out of the tunnel.

A certain amount of leakage will occur through the dike when it is bulkheaded. The stream flow measurements in Table 2, the flow of 1.5 mgd between stations 6 + 00 and 9 + 80 during construction and recent measurements showing a gain in flow between these stations of about .07 mgd on April 24th, indicate that leakage definitely occurs. It is very likely that this water can be used by the Navy at Haiku. Before construction of the tunnel, leakage through the dike at 980 feet had to occur in order to supply base flow to Haiku stream. Without the new bulkhead and a build up in storage, the nature and extend of this leakage cannot be well defined.

The merits of ground water storage in dike compartments has proven to be a very effective means of providing high rates of flow to the system during peak periods of demand as demonstrated by Waihee tunnel. Reconstruction of Haiku tunnel should prove a valuable addition to peak capacity flows, particularly when the pipeline to Hawaii Kai is completed. Sufficient time should be permitted for the construction of the new bulkhead and for the rebuilding and testing of the storage. Bulkhead construction should begin in the spring of 1970.

REFERENCES

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MINK, J. F., 1962, The Hydrology of Waihee Tunnel and Upper Waihee Valley, Board of Water Supply manuscript report.

TAKASAKI, K. J., HIRASHIMA, G. T., LUBKE, E. R., 1969, Water Resources of Windward Oahu, Hawaii, U. S. Geological Supply Paper 1894.

HAIKU VALLEY PROFILE

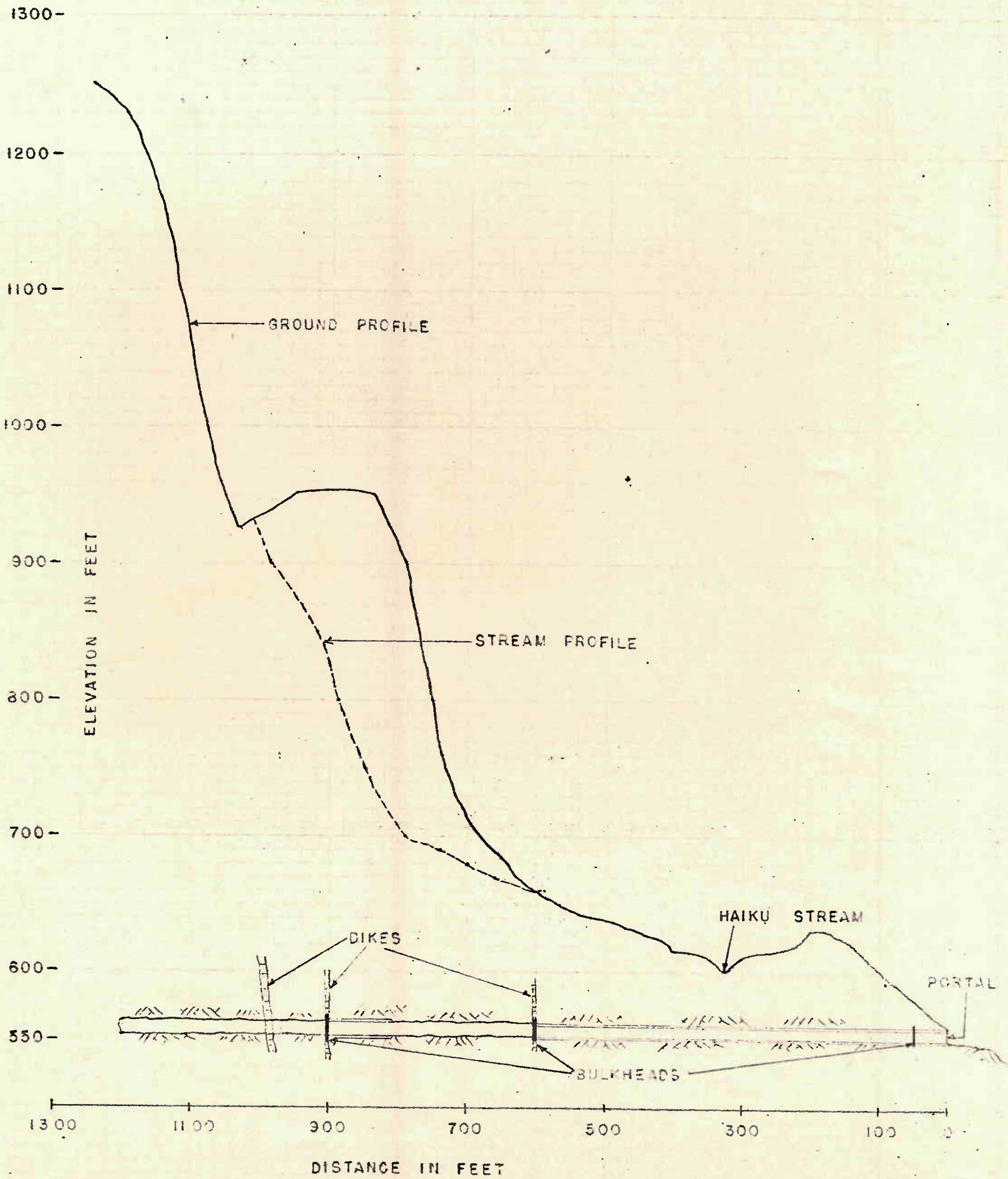


FIG. I

HAIKU TUNNEL PLAN

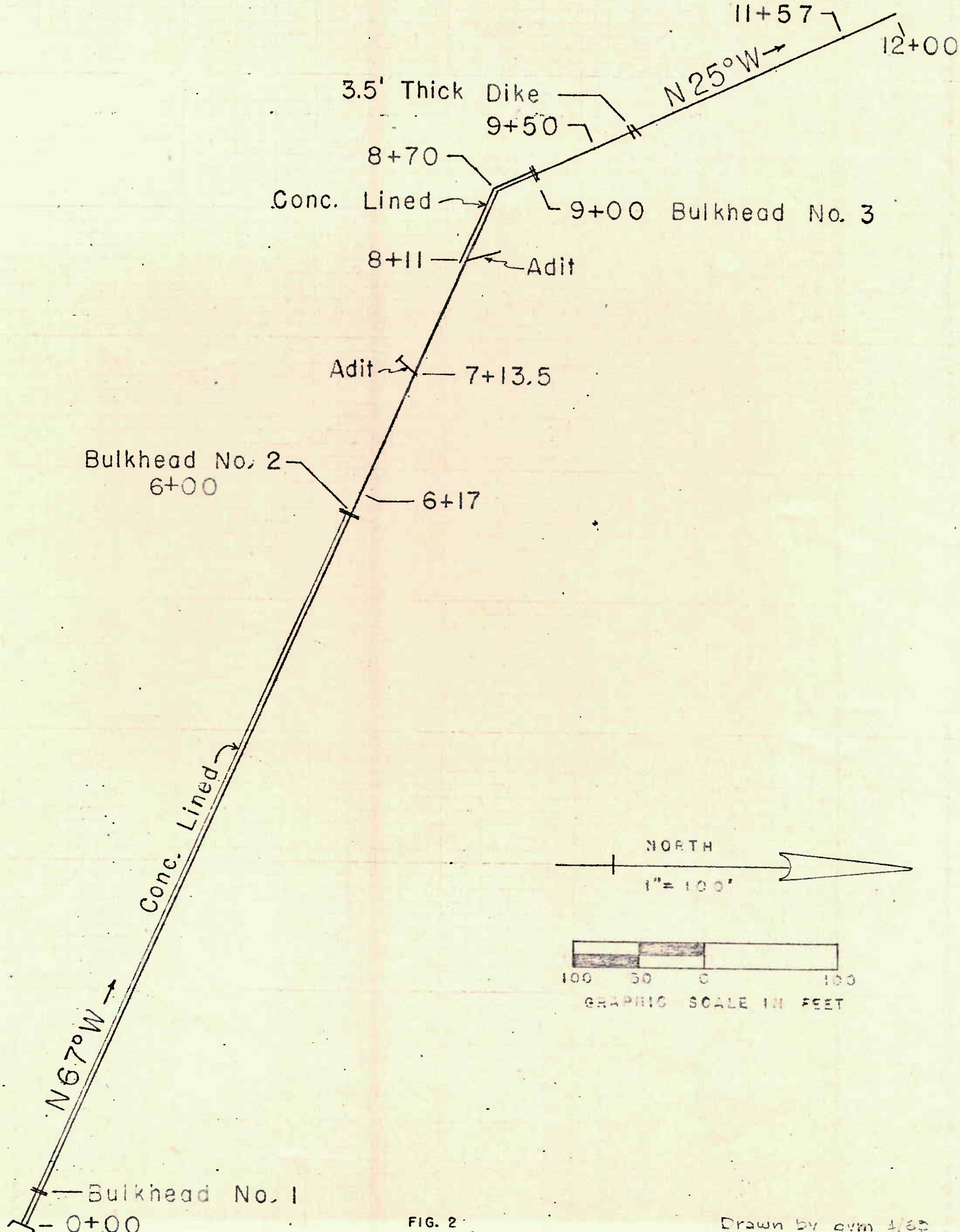


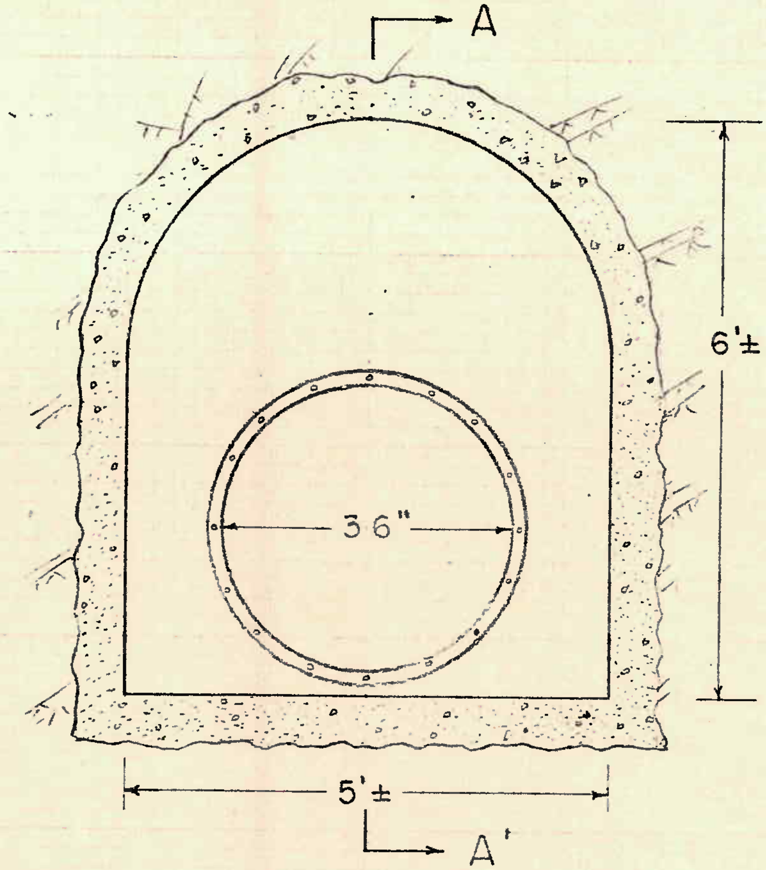
FIG. 2

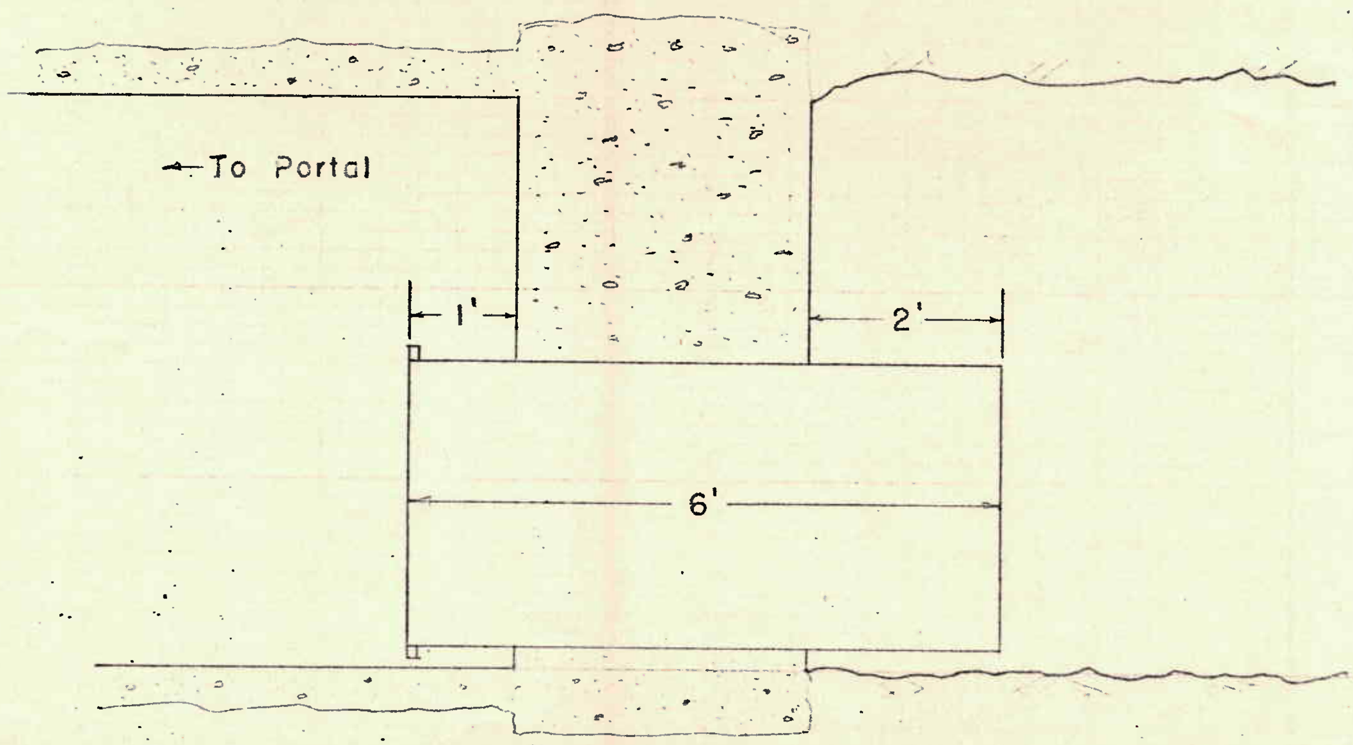
Drawn by gym 4/65

BULKHEAD No. 2

Station 6+00

Scale: 1" = 20'





SECTION AA'

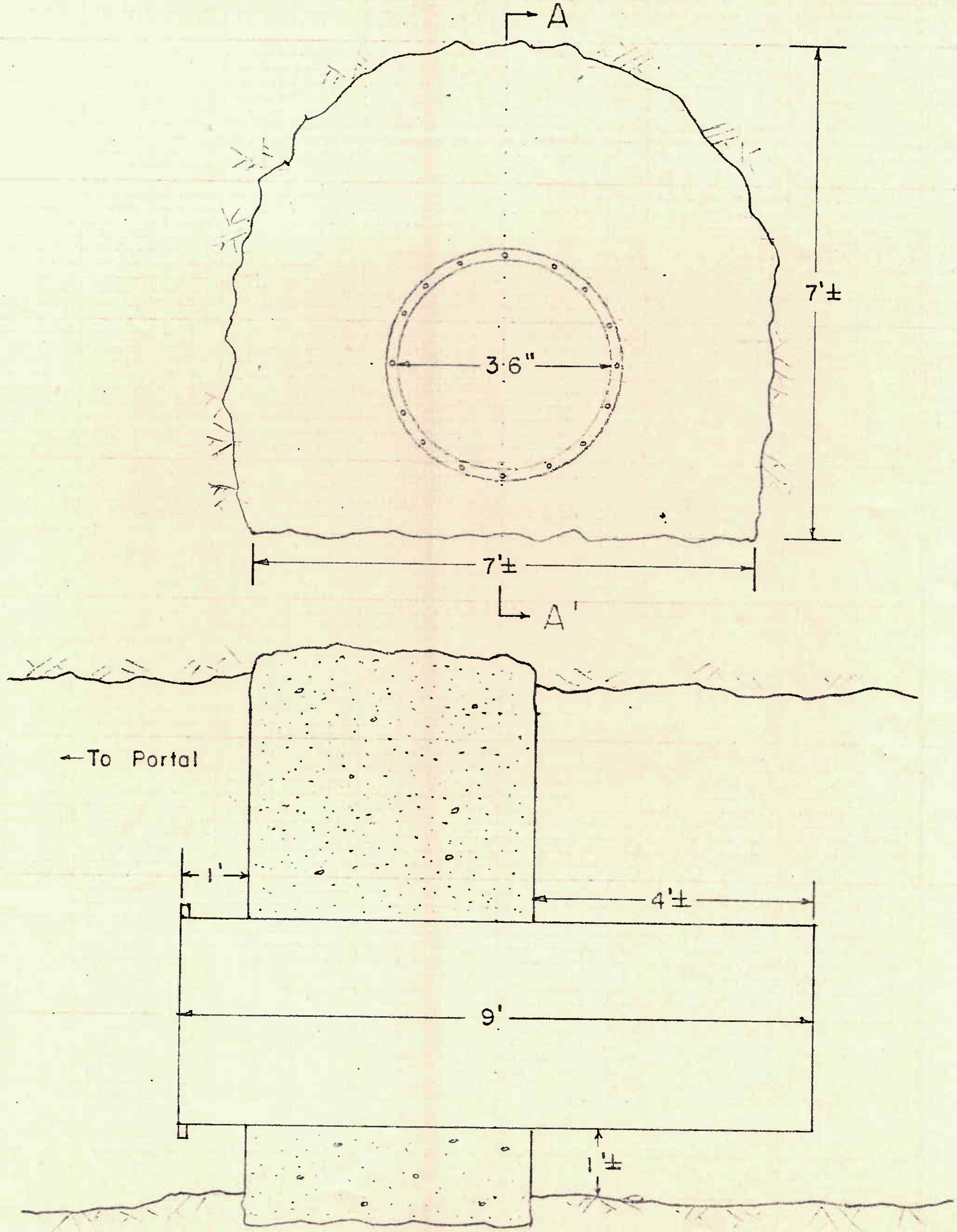
4/69 gym.

FIG. 3

BULKHEAD No. 3

Station 9+00

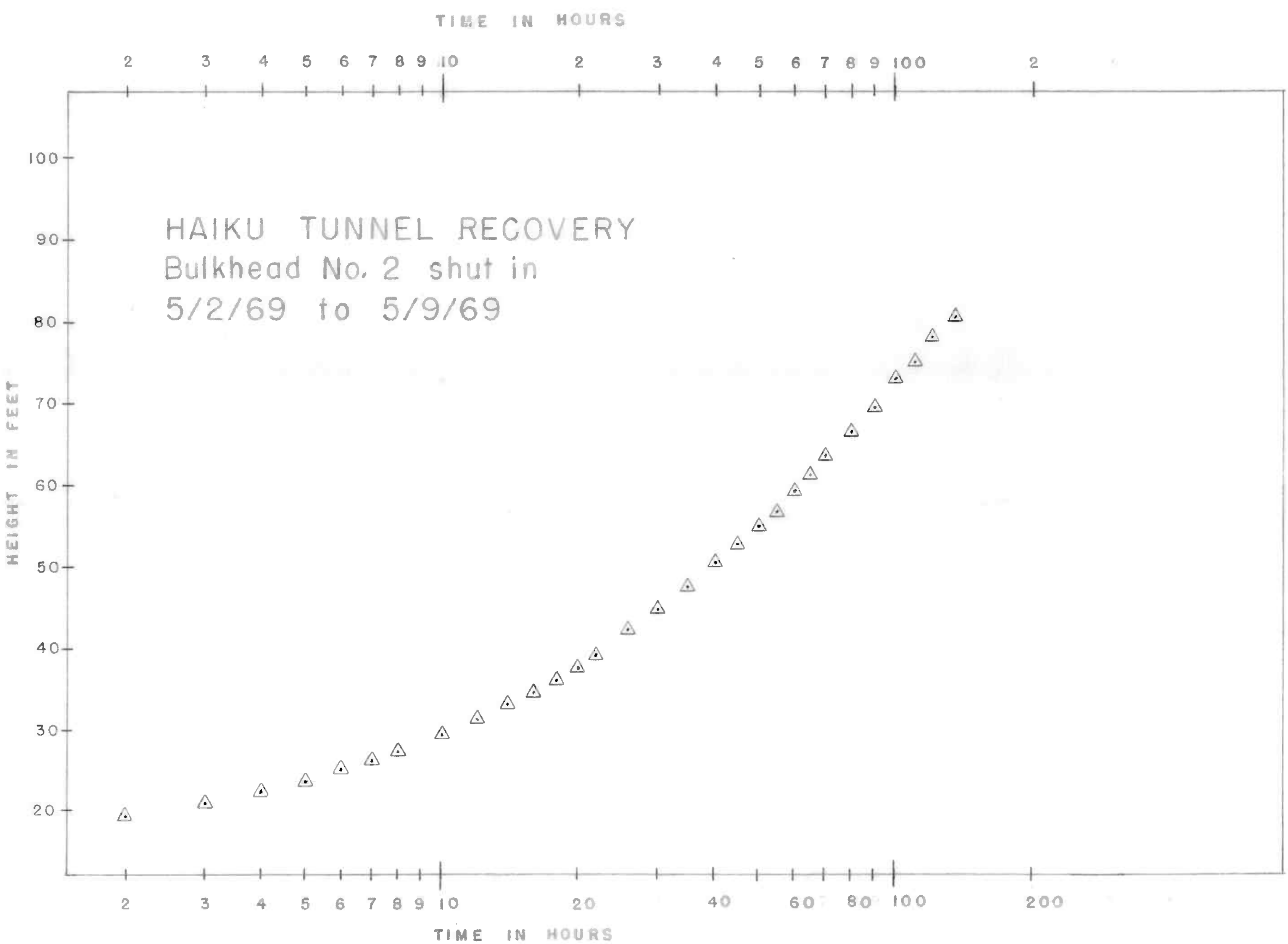
Scale: 1" = 20'



SECTION AA'

FIG. 4

4/69 g.y.m.

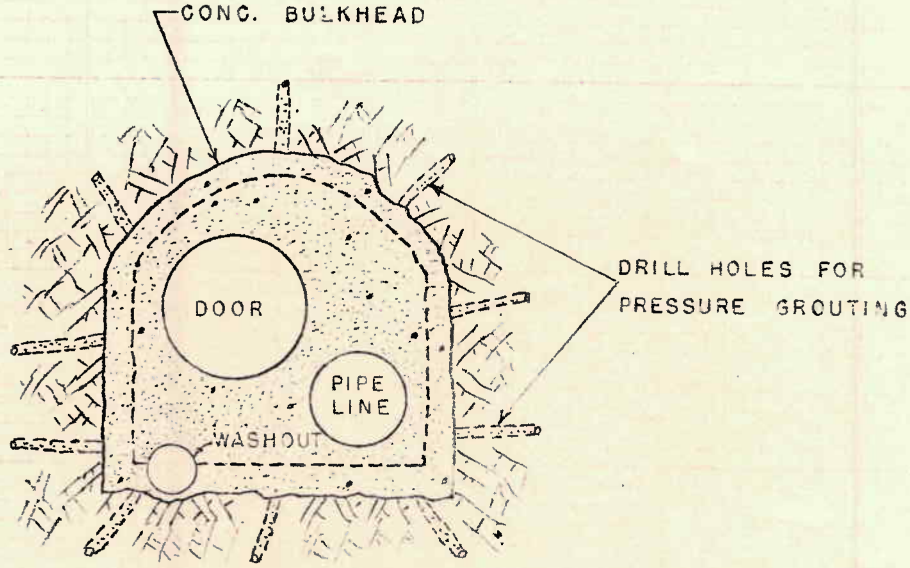


TIME IN HOURS
2
3
4
5
6
7
8
9
10
2
3
4
5
6
7
8
9
100
2
HAIKU TUNNEL RECOVERY
Bulkhead No. 2 shut in
5/2/69 to 5/9/69
HEIGHT IN FEET
100
90
80
70
60
50
40
30
20
2
3
4
5
6
7
8
9
10
20
40
60
80
100
200
TIME IN HOURS

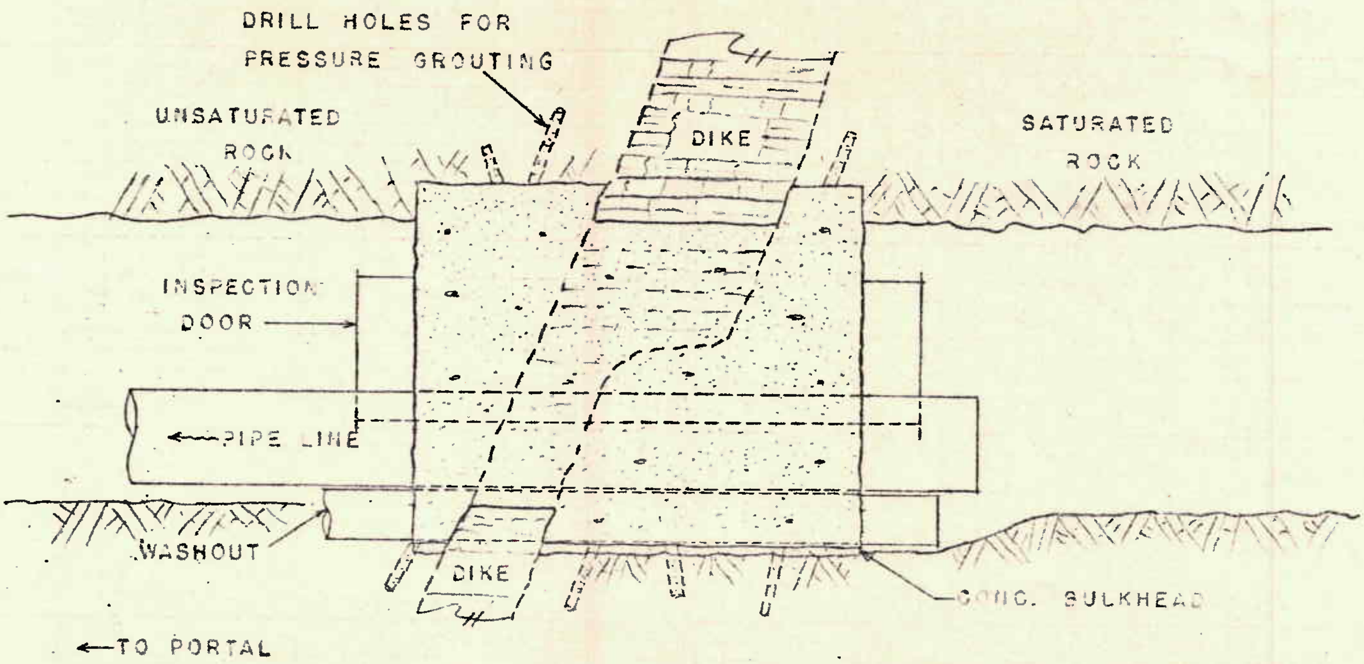
FIG. 5

PROPOSED BULKHEAD NO. 4
AT STA. 9+80

SCALE: 1" = 4.0'



FRONT VIEW LOOKING UP TUNNEL



SIDE VIEW

6/63 g.y.m.

FIG. 6

HAIKU STREAM

Flow Measurements in MGD*

Sept. 21, 1938

Station	Altitude	Stream Flow
1	682	.228
2	654	1.10
3	616	.918
4	547	1.18
5	460	1.16
6	446	1.18

*Water Supply Paper 885 pg. 54

TABLE 1

HAIKU TUNNEL

Flow Measurements in MGD
(current meter)[1]

April 1969

Station	4/9	4/10	4/11	4/14	4/18	4/21
11 + 57			1.36	1.32		
9 + 50	2.43	2.63	2.43	2.40	2.36	2.36
6 + 17[5]					2.59	2.44

Notes: 1. All measurements made using Pygmy current meter (Current meter No. 271596) and stop watch.

2. 4/22/69 - Pressure at head of tunnel as measured in drill hole was 23 psi.

TABLE 2

APPENDIX G

COMMISSION ON WATER RESOURCE MANAGEMENT NOTICE OF COMMISSION ACTION

STATE OF HAWAII
DEPARTMENT OF LAND AND NATURAL RESOURCES
COMMISSION ON WATER RESOURCE MANAGEMENT
P.O. BOX 621
HONOLULU, HAWAII 96809

June 18, 2021

Ref: PAIFS.5666.3

Ernest Y.W. Lau, P.E.
Manager and Chief Engineer
Honolulu Board of Water Supply
630 S. Beretania Street
Honolulu, HI 96843-0001

Aloha Mr. Lau:

NOTICE OF COMMISSION ACTION
Order to Honolulu Board of Water Supply to Bulkhead
Ha'ikū Tunnel (Well No. 2450-001) at the 10-foot Thick Dike 1,200 feet
From the Portal Entrance and Reduce Their Withdrawal to 0.3 million gallons per day
<u>He'eia Hydrologic Unit, Ko'olaupoko, O'ahu</u>

This letter serves as your notice of action taken by the Commission on Water Resource Management (Commission) on the subject matter. On June 15, 2021, by a 7-0 vote (1 vote for approval with reservations), the Commission approved the following Order:

He'eia Stream supported one of the most agriculturally productive areas on O'ahu. The Ha'ikū Tunnel, dug at an elevation of 550 feet, depleted the groundwater storage of high-elevation dike compartments which supplied baseflow to He'eia Stream. In 1971, the USGS recommended that bulkheading at a 10-foot thick dike compartment at approximately 1,200 feet from the tunnel entrance is the preferred method to restore the storage function of the aquifer. Tunnels with high recession constants (*b*), such as the Ha'ikū Tunnel, drain faster than tunnels with lower recession constants, and would therefore benefit more from bulkheading. An existing bulkhead installed and valved at 600 feet from the portal provides some small storage. The substantial ecological and cultural values supported by He'eia Stream, including habitat for native amphidromous species, restored native riparian environment, a healthy estuarine and near-shore ecosystem, recreational and aesthetic values, as well as the productivity of the He'eia fishpond and wetland to support a biocultural food production system, merits restoration of He'eia Stream to pre-tunnel baseflow. In order to protect these instream uses staff recommends that Honolulu Board of Water Supply (HBWS) bulkhead the 10-foot thick dike compartment at approximately 1,200 feet from the tunnel entrance and valve separately from the bulkhead at 600 feet from the tunnel entrance. Such action would increase spring flow in Ha'ikū while providing a more reliable source of water supply for HBWS. This solution is expected to increase the natural capacity of the high-elevation groundwater system to store and discharge water to streams and springs in the moku of Ko'olaupoko.

As an interim measure, until the Ha'ikū tunnel is fully bulkheaded, Commission staff recommends that HBWS reduce their withdrawal from the Ha'ikū tunnel to 0.3 million gallons per day (mgd) by August 15, 2021. When the bulkheading process commences, the Ha'ikū tunnel will not be a viable source for HBWS, and therefore the entirety of the tunnel flow will be discharged into the stream.

In order to improve transparency among stakeholders, staff recommends that HBWS provides the daily amount of water withdrawn from each well source (Ha'ikū Tunnel, Ha'ikū well, and Ioleka'a well) at monthly intervals.

Following the bulkheading of the tunnel, staff will evaluate the resultant effects on stream baseflow and may amend the interim IFS or amend the HBWS water use permit as needed.

<u>IMPLEMENTATION</u>

- Within two years, HBWS will complete their feasibility study and preliminary engineering design for the proposed bulkhead.
- HBWS will communicate with the Commission and continue to coordinate with Kamehameha Schools, Department of Hawaiian Home Lands (DHHL), Papahana Kuaola, Hawai'i Community Development Authority (HCDA), National Estuarine Research Reserve (NERR), and Kāko'o 'Ōiwi water users on a quarterly basis.
- Upon completion of the feasibility study and engineering design, HBWS will have three years to complete the final design and construction of the bulkhead.
- Following the installation of the bulkhead, staff will work with HBWS, Kamehameha Schools, DHHL, Papahana Kuaola, HCDA, NERR, and Kāko'o 'Ōiwi to evaluate the implications for baseflow in Ha'ikū Stream and determine the feasibility of establishing a numeric instream flow standard.
- If HBWS determines that bulkheading is not a feasible solution upon completion of the feasibility study, staff will recommend an amendment to the interim IFS or amend the HBWS water use permit as needed.

<u>MONITORING</u>

- Streamflow monitoring shall be maintained by HBWS coordinating with USGS.
- At monthly intervals, HBWS will provide monitoring of daily flow withdrawn from the Ha'ikū Tunnel, Ha'ikū well, and Ioleka'a well.
- Periodic biological surveys shall be conducted, subject to available funding, to monitor the response of stream biota by all interested parties.
- All claimants shall cooperate with staff in conducting appropriate investigations and studies, particularly with regard to granting access to stream channels and private property related to such investigations, subject to the provisions of the State Water Code, Chapter 174C, HRS.

EVALUATION

- One to two years following the completion of the bulkheading, staff shall report to the Commission on an evaluation of baseflow conditions in He'eia and nearby streams and make recommendations to amend instream flow standards at that time.

Staff will report to the Commission, at its September 2021 meeting, on the progress of:

1. HBWS reduction to 0.3 mgd from Ha'ikū Tunnel;
2. HBWS reduction from Ha'ikū Tunnel to flow in He'eia Stream;
3. Assessment of bulkhead feasibility and preliminary engineering report; and
4. Potential development of alternative water sources, including the State Hospital Well.

If you have any questions, please contact Ayron Strauch at (808) 587-0265, or ayron.m.strauch@hawaii.gov.

Ola i ka wai,

M. KALEO MANUEL
Deputy Director