ERDC/CHL SR-00-2

Coastal and Hydraulics Laboratory

US Army Corps
of Engineers®
Engineer Research and
Development Center

Channel Stability Problems, Iao Stream, Maui, Hawaii

U.S. Army Engineer Committee on Channel Stabilization
Report of the 64th Meeting—September 1999

Ronald R. Copeland and Dinah N. McComas, editors

June 2000

ERDC/CHL SR-00-2
CCS-00-2
June 2000

Channel Stability Problems, Iao Stream, Maui, Hawaii

U.S. Army Engineer Committee on Channel Stabilization Report of the 64th Meeting—September 1999

by Ronald R. Copeland and Dinah N. McComas, editors

Coastal and Hydraulics Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Final report

Approved for public release; distribution is unlimited

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Engineer Research and Development Center Cataloging-in-Publication Data

United States. Army. Corps of Engineers. Committee on Channel Stabilization. Meeting. (64th : 1999 : Maui, Hawaii)

Channel stability problems, Iao Stream, Maui, Hawaii : U.S. Army Engineer Committee on Channel Stabilization report of the 64th meeting, September 1999 / by Ronald R. Copeland and Dinah N. McComas, editors ; prepared for U.S. Army Corps of Engineers.

51 p. : ill. ; 28 cm. -- (ERDC/CHL ; SR-00-2)(CCS ; 00-2)

Includes bibliographic references.

1. Iao Stream (Hawaii) 2. River channels -- Hawaii. 3. Channels (Hydraulic engineering) -- Hawaii. 4. Flood control channels -- Hawaii. I. Copeland, Ronald R. II. McComas, Dinah N. III. United States. Army. Corps of Engineers. IV. Engineer Research and Development Center (U.S.) V. Coastal and Hydraulics Laboratory (U.S.) VI. Title. VII. Series: CCS ; 00-2. VIII. Series: ERDC/CHL SR ; 00-2.

TA7 E8 no.ERDC/CHL SR-00-2

Contents

Executive Summary

The U.S. Army Engineer District, Honolulu, requested the participation of the U.S. Army Engineer Committee on Channel Stabilization in a joint review of channel stability and levee undermining problems in Iao Steam, Maui, Hawaii (Appendix A). The Committee was asked to review problems associated with the stream and provide cost effective structural and nonstructural recommendations.

Objectives and Constraints

Project objectives and constraints were presented to the Committee by the Honolulu District and Maui County personnel.

a. The flood control project is to provide Standard Project Flood level of protection. This objective is consistent with the original project design.

b. Maintenance costs must be minimized because resources available for project maintenance are decreasing.

c. Aesthetics are important in this urban environment. It is desirable to avoid conventional concrete channelization.

d. It is important to maintain habitat and provide for fish passage. This requires maintaining a low flow channel with a capacity of between 5 and 10 cfs. Relief on drop structures makes fish passage more feasible. Relief on the channel bottom provides diversity beneficial to organisms. Standing water should be minimized as it provides unfair advantage to less desirable predators from higher in the food chain. Shade should be provided over the low flow channel. Groundwater recharge is desirable.

e. The project must be cost effective. A positive benefit cost ratio is required.

f. Channel expansion on the right descending bank is infeasible due to existing levees. However, the only width constraint on the left side of the channel is in the vicinity of station 43+00 where a historic Heiau (temple) is located on an adjacent hill. Otherwise widening is feasible on the left side of the channel.

Active Natural Processes

The Committee identified the significant natural processes that are currently adversely affecting flood damage reduction on Iao Stream.

a. Flow tends to concentrate along the base of the levees causing the most severe erosion potential to occur at the most vulnerable location – the levee toe. This occurs due to the relative smoothness of the levee when compared to the rest of the channel perimeter. The presence of vegetation and bed and bank irregularity are responsible for greater hydraulic roughness in the rest of the channel.

b. Local scour occurs along the levee at points of impingement due to natural meandering and due to changes in channel alignment.

c. Local scour occurs in the vicinity of Station 43+00 due to channel constriction.

d. Generalized degradation and headcutting are occurring due to the cutoff of sediment supply from the upstream watershed by the sediment basin.

e. Maintenance practices may actually increase the rate of degradation. Large flow events tend to establish a coarse surface area (armor) on the streambed. This armor layer, established by winnowing of the finer material as the channel degrades, protects the stream from further degradation or at least slows the process. However, if this coarser material is pushed up against the banks, then the degradation process would continue.

f. Gravel mining that removes the coarser surface layer and/or leaves an effective in-channel sediment trap can lead to degradation.

Geotechnical processes that contribute to bank, slope, and embankment instability, failure and failed-soil erosion are complex and include erosional oversteepening and undercutting with related upslope failures during periods of rainfall and high flows. As the stream recedes from high stages more rapidly than bank and embankment soils can drain, loading causes slumping and collapse. Seepage exit and internal erosion, or piping, cause cavity formation, and result in cantalevering, tension crack propagation and slabbing or block failures. Berms of failed soils and displaced cobbles and boulders shed secondary currents during moderate and high flows and cause additional erosion of inplace soils. Stream channel degradational processes increase vertical extents of rapid recession and groundwater gradients. Bed degradation outflanks weephole systems with renewed piping along undercut slopes. Collapse of overhanging grouted stone and concrete, and placement of boulder berms, do not address seepage related processes or stabilize existing failures.

Additional processes were identified that would be active during a future large flood, including the design flood.

a. Filling of the sediment basin and sediment transport downstream that could reduce the channel conveyance downstream, both by cross-sectional area reduction and increased hydraulic roughness.

b. The levees will induce some additional degradation over natural conditions because flow on the floodplain has been prevented and more flow will be concentrated in the channel.

c. Return flow from the left overbank near station 43+00 will induce additional local scour at a location already subject to local scour due to impingement and constriction. Headcutting back into the floodplain can be expected from the return flow.

Recommended Engineering Evaluations

These additional studies were recommended to obtain a more concise understanding of the currently active natural processes in Iao Stream and/or to provide information that would be used in the channel design.

a. A computationally stable hydraulic backwater computation (direct step) should be made to determine hydraulic parameters in the design channel. Supercritical flow typically cannot be maintained for any length of time in an alluvial channel. Minimum depths for channel design or overflow analysis should be set at 1.1 times critical depth.

b. The bed-surface gradation of the existing channel bed should be determined. This can be accomplished by extending a measuring tape along the streambed and sampling at regular intervals (Wolman count). The bed-surface gradation would be used to determine critical shear stress in the existing channel and would be useful in determining the design shear stress for a threshold channel.

c. Determine the hydraulic roughness coefficient for boulder concrete using data from the U.S. Geological Survey gauges in the upper portion of the flood control channel.

d. A study to assess the causes and identify the progression of degradation in the existing channel should be conducted. This study should include a survey of the thalweg profile to compare with as-built and/or preproject profiles. The survey should also locate grade control structures, constrictions, impingement points, and zones of maintenance activity. Although the numerical sedimentation model, HEC-6, is not designed to model sediment of the size found in Iao Stream, a qualitative assessment of what to expect during a design flood could be achieved with a numerical model simulation.

e. Do an analysis to determine sediment yield to the existing sediment basin for a range of flood events, including an event with a major landslide in the watershed. This analysis should determine both the quantity and gradation of sediment, so an analysis of trap efficiency and potential deposition in the flood control channel can be made.

f. Streambank slope stability should be re-evaluated for failure by slope oversteepening and rapid recessional loading. The existing levee failure analysis as presented to the Committee is adequate for economic analysis but not for design.

Design Objectives

These are specific channel design objectives based on the general project objectives and constraints previously stated, and on the constraints imposed by the natural processes.

a. Fully protect the right bank upstream to downstream to provide reliable protection from the Standard Project Flood (SPF). The top of levee elevation must be sufficient to contain the design flood computed using the greater of 1.1 times the critical flow depth or the subcritical backwater elevation. Bank protection up to the calculated SPF water-surface should be constructed using either roller-compacted concrete, grouted stone, or reinforced concrete. The upper levee surface may be protected using graded riprap or vegetation. Allowable shear stress methods can be used to size riprap and/or select appropriate vegetation species.

b. Provide bed stabilization to control degradation. This can be accomplished using a fully armored bed or grade control structures.

c. Provide bank stabilization to the left bank to protect the bed stabilization and to prevent channel irregularity and meandering. Grade control structures or stabilizers should be keyed into the left bank, and protection provided for an appropriate distance upstream and downstream from the structure. Erosion scarps and channel protrusions should be removed. In some cases full bank protection may be required. In other cases toe or toe and lower bank protection may be adequate.

d. Slope stabilization should be provided for the unprotected banks. This could include removal of material behind the failure surface and regrading. Slope stabilization could also be attained by buttressing, retaining structures, and/or foundation drainage.

e. Provide an inlet structure to return left overbank flows to the channel during the design flood.

Design Concepts

The following figures provide conceptual designs that meet the design objectives. One design (Figures 1 and 2) is for a partially armored bed at the existing slope. It features a semipervious center section armored with large derrick stone. The second design (Figures 3 and 4) consists of grade control structures that reduce the slope to the point where a pervious natural bed is possible. The second design concept is expected to be more expensive to construct.

A combination of design concepts may be preferred. For example, the constricted reach extending for about 0.5 mile upstream from Waiehu Beach Road may require a supercritical concrete channel while a wider, subcritical design could be used upstream from the constricted reach.

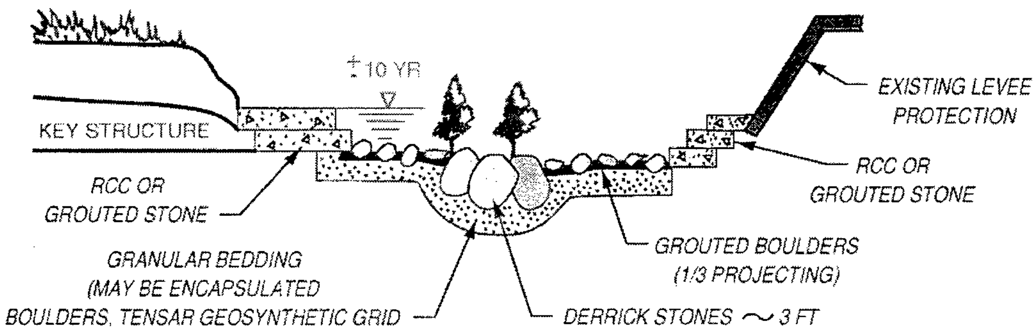

Figure 1. Cross section of armored channel adjacent to existing levee

Key structures would prevent flanking at high flood flows. Cross channel grade control sills should also be included as a safety feature. Keys and grade control should be spaced between 200 to 500 ft.

General Conclusions

The Committee on Channel Stabilization concluded that the current Honolulu District plan calling for a reinforced concrete channel in the existing alluvial reach is a sound reliable engineering design. It may also prove to be the most cost effective. The Committee concurs with the District's conclusion that a "hard" engineering solution is required to meet the design objective of Standard Project Flood protection. The alternative design concepts developed by the Committee will also meet the flood damage reduction objective, while also meeting some of the environmental and social objectives. It is left to the District to determine cost effectiveness.

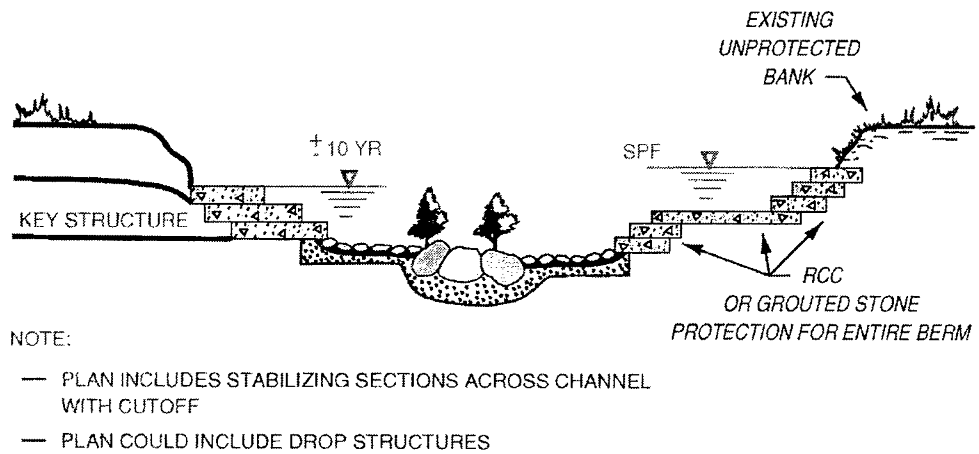

Figure 2. Cross section of armored channel adjacent to unprotected bank

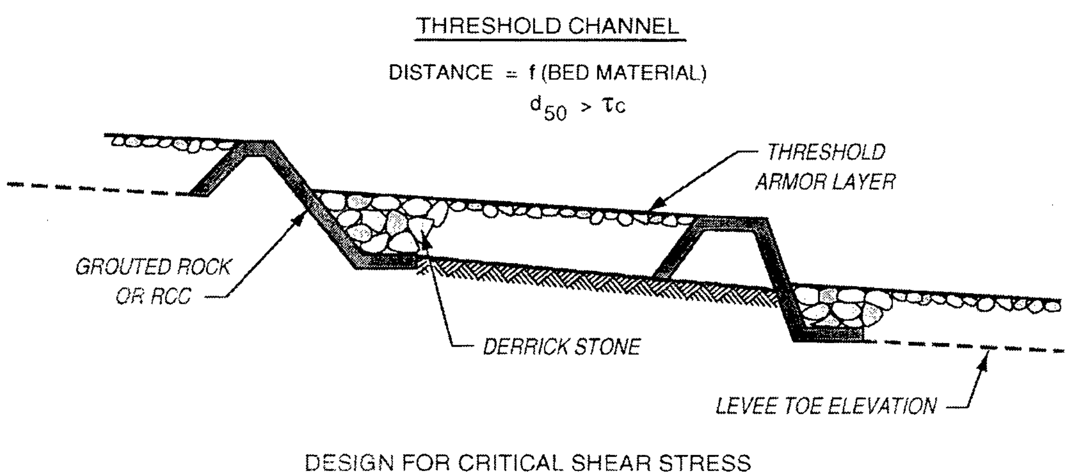

Figure 3. Profile of threshold channel design with slope reduced by drop structures

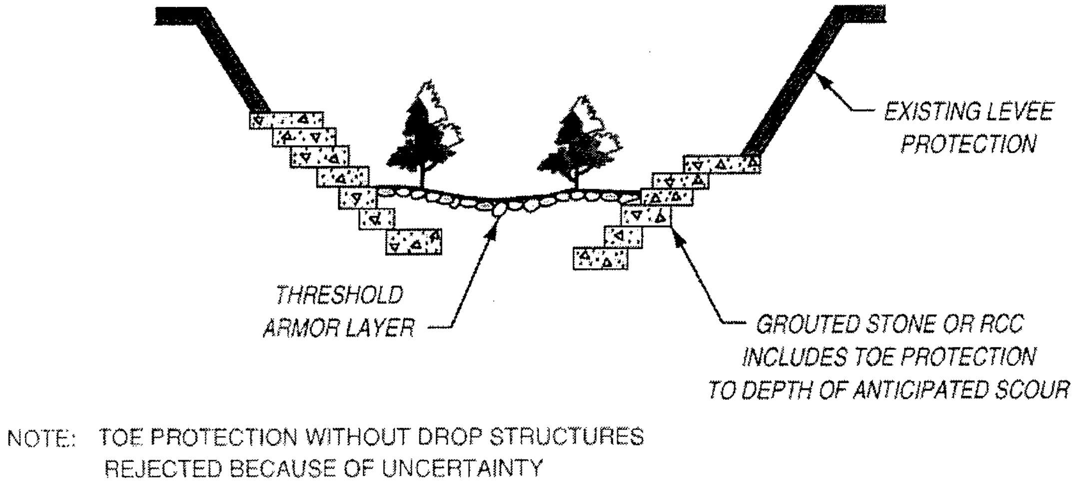

Figure 4. Cross section of threshold channel design

Figure 5. Committee on Channel Stabilization Iao Stream, Maui, Hawaii

Attendees

U.S. Army Engineer Committee on Channel Stabilization

Larry Banks, CEMVK-ED-H
Ronald Copeland, Chairman, CEERDC-HR-R
Craig Fischenich, CEERDC-EE-A
Margaret Jonas, CENAB-EN-GH
Jim Lencioni, CENPS-ED-TB-HH
Dinah McComas, Secretary, CEERDC-HR-R
Tom Pokrefke, CEERDC-H-M
John Remus, CENWO-ED-HB
Mike Spoor, CELRH-ED-GH
Scott Stonestreet, CESPK-ED-D
Howard Whittington, CESAM-EH-H

U.S. Army Engineer District, Honolulu

James Pennaz, CEPOH-EC-T
Sharon Ishikawa, CEPOH-PP-C

County of Maui, HI

Francis Serezo, Department of Public Works
Lloyd Lee, Chief Engineer
Eddie Emoto, Maintenance

1 Introduction

Jim Lencioni

Senior Hydraulic Engineer
U.S. Army Engineer District, Seattle

The 64th meeting of the Engineer Committee on Channel Stabilization (CCS) was held at the request of the U.S. Army Engineer District, Honolulu, on 14-16 September 1999. The Committee convened to review and offer guidance on design modifications to the Federally-designed and constructed Iao Stream Flood Control Channel Project located near Wailuku County in Maui, Hawaii.

The existing flood control project was constructed in 1981. At the upstream end of the project is a debris basin designed to capture most of the watershed's sediment load. Downstream from the debris basin is a boulder-concrete channel approximately 1,100-ft-long. This fully-lined channel has several chutes and a vertical drop structure at its downstream end. Downstream of the drop structure is 200-ft-long reinforced concrete channel followed by a 7,000-ft-long reach of alluvial channel. The alluvial channel reach has levees on its right bank to protect the town of Wailuku. This alluvial reach is where stabilization problems are occurring and is the focus of this report. The final 1,700 feet of the project is a rectangular concrete-lined channel with a boulder-concrete bed and conventional reinforced concrete side slopes. The flood control project was authorized and designed to provide a Standard Project Flood (SPF) level of protection (26,500 cfs at the mouth).

The Iao Stream has a drainage basin of about 10 square miles and is subjected to rather short duration, high intensity rainfall events and significantly large sediment loads. The maximum discharge experienced since completion of the federal project is about 4,100 cfs, significantly less than the design discharge. HEC-RAS computations furnished by POH indicate that average channel velocities through the natural portion of the channel range between about 8 and 32 fps during a project design discharge event with average velocities in excess of 20 fps at most places in the natural reach. The project's debris basin has been rather efficient in preventing movement of large sediment volumes through the concrete-lined channel but has been surmised to create scouring in the natural channel downstream as a result of deprivation of the channel's natural sediment load. Since completion of the project, the bed in the downstream 4,000-ft reach of natural channel between the two concrete-lined segments has experienced typical scour of approximately 3 ft with maximum localized scour depths on the order of 8 ft. The bed in the upstream reach of the natural channel does not appear to have suffered significant scour to date. The scour in the downstream portion of the natural channel is presently threatening the integrity of the levees in numerous locations and subsequently significantly impacting the reliability of the Federally-constructed project. The existing damage is most disturbing considering the low discharges experienced compared to the project's design discharge. The local sponsor has been very active in attempting to maintain the project's integrity by removing sediment deposits and strengthening the levee toe with large boulders. However, conditions have progressed to the point where their resources are not able to accomplish the works necessary to ensure the reliability of the project.

POH is investigating a project modification to stabilize the eroding natural channel portion of the project. Preparation of a design memorandum (DM) and environmental assessment (EA) was initiated in January 1996. Three structural plans of improvement have been developed for the DM. These plans include two alternatives of conventional trapezoidal concrete-lined channels (two different alignments) and an alternative consisting of a wide, compound conventional concrete channel with grassing within. A majority of the Maui County Planning Commission voiced strong opposition to any plan utilizing a concrete channel and favored a more natural appearing channel solution.

In its request for review of the project design by the CCS, POH requested the Committee focus on the following objectives:

a. Determine what area(s) would be subject to levee failure.

b. Determine how much failure can be expected with various flows.

c. Provide a cost effective solution to the erosion problem.

d. Provide a design that solves the erosion problem but does not significantly degrade the environment nor include concrete channelization. If such a solution does not exist, document the reason(s) why.

A visual inspection of most of the Iao Stream was made beginning at its mouth and extending upstream to the debris basin. An approximately 1,000-ft-long reach of the natural channel between about Stations 65+00 to 75+00 was not observed. The remaining 6,000 ft of the natural channel portion of the project was walked. The two concrete reaches of the project are in good condition and should have no problem safely handling the project design flood. The natural channel portion of the project and the existing levees protecting the town of Wailuka, on the other hand, are in a serious state of instability and would undoubtedly fail and result in loss of project reliability and extensive flooding at discharges well below the project design discharge.

Bed scour of up to 8-10 feet has occurred in the downstream mile of the natural channel and has resulted in failure of portions of levee embankment. Some areas exhibited levee embankment erosion well into the structural prism of the original levee cross section. The existing bed is composed of large boulders and gravel. Bed material size distribution information is not available. However, it appears that a large portion of the surface layer is greater than 12 in. and numerous stones on the order of 3 to 4 ft in diameter were observed. The size of material which has been in motion gives a deep appreciation for the energy involved in this stream system. The bed instability existing in the downstream reach of the channel appears to be similar to development of a head cut that has not yet moved the entire length of the natural channel. Continuing high discharges would likely cause scour similar to that existing in the downstream reach to eventually extend upstream to the upstream concrete-lined channel portion of the project. Therefore, the integrity of the entire length of the levee protection, and subsequently the authorized level of protection provided by the project, is in jeopardy.

2 Committee Comments

Larry Banks

Chief, Hydraulics Branch
U.S. Army Engineer District, Vicksburg

The following comments are made relative to questions raised by Honolulu District concerning the Iao Stream Project, Maui, Hawaii.

Concerning the potential for failure of the levee system and delineation of the area subject to flooding from levee system failure, I believe the present system would definitely not be capable of safely passing the project design flood (SPF) on Iao Stream. I have personally reconned areas in the southern United States (on non-Federal levees) where levee systems similar in size, head differential, and general composition of materials to Iao Stream experienced catastrophic failures. These levees were on streams with much milder slopes having stream velocities less than 7-8 fps. Iao Stream velocities for the design flood are above 25 fps. I believe the excessive channel velocities on Iao Stream will be sufficient to erode the levee material even for events much less than the design event (as has already been proven in some past events). Therefore, I concur with the analysis by the District that for all practical purposes in a major flood event, the majority of the protected area would be likely to flood. This supports the rationale for the design deficiency which has been declared for this project. I also believe that any alternative to be considered in response to this design deficiency must include means to effectively prevent movements of sediment in the channel and on the levee slopes. Such means could include a reinforced concrete channel design such as that proposed by the District or an alternative design such as that proposed by the Committee on Channel Stabilization.

In considering a cost-effective and environmentally sensitive alternative to the concrete channelization proposed by the District, I believe the concept proposed by the Committee on Channel Stabilization and discussed in this report would be more cost effective and environmentally and aesthetically pleasing than a conventional concrete channel and levee system. The proposed system accomplishes the requirement for having an "immobile" bottom and levee slope material, provides some diversity in the low-flow channel which could (and should) be allowed to support low-level vegetative growth, allows some potential for groundwater recharge, and is compatible with the remainder of the flood control system upstream which limits the intrusion of large sediments into the downstream flood control system.

Some specific areas that should be addressed in the short term are the need to realign the channel immediately below the point where the left descending overbank widens (near Heiau – Sta 0 on Levee B). The bar on the left bank of the channel appears to have grown causing additional scour on the right bank and thus may be contributing to severe undermining of the levee during intermediate flow events. A temporary fix to this problem, which might buy some time in the effective life of the levee, would be to remove the bar on the left bank of the channel and place material as a berm on the right toe of the levee and channel. Some protection over this, grouted rock or large boulders, would need to be accomplished to further protect the berm.

Another area where immediate temporary repair of the levee is needed is where significant undermining of the levee and degrading of the channel has occurred (site at which group photo was made). At this location, a boulder and/or grouted stone grade control across the channel could easily be constructed to tie with the overhanging grouted stone bank protection. This might slow the degradation in this reach for intermediate floods which may occur in the interim period until a more comprehensive repair of the entire system is initiated. However, I firmly believe these types of repairs would not suffice to protect the town if an event of the magnitude of the design flood were to occur.

A few observations which need to be considered as subsequent analysis and design of a more permanent repair of the levee system progresses are discussed below:

a. The old maps show that the levees are built along an alignment that was originally agricultural ponds. The materials underlying the present levee system should be reviewed to ensure they are compatible with good levee material. (I did not see any evidence of borrow construction in the area and hope that the base of the levee system did not come from the channel system material).

b. In consideration of a possible option of a series of many grade control structures on the channel, I believe the spacing of structures required to achieve effective control of degradation on the system will be so short that this type of protection would not be warranted. A system of immovable protection using criteria for a chute type drop system would be better in this instance. For this flood control system, this design concept would likely evolve into the combination grouted rock and/or roller-compacted concrete channel and levee with a boulder stone low flow channel as described elsewhere in this report.

Ronald Copeland
Research Hydraulic Engineer
Coastal and Hydraulics Laboratory
U.S. Army Engineer Research and Development Center

Grouted stone drop structures

Grouted stone drop structures have performed satisfactorily on the San Gabriel River in Los Angeles County for over 30 years. This river is a cobble-boulder bed stream with a pre-project slope in the project reach of about 0.0125. The channel was designed using maximum velocity criteria. A maximum velocity of 10 fps was selected to allow for only minor transport of fine streambed material and to minimize the potential for toe scour against the levees. Drop structures were placed about 1,000 ft apart providing a project slope of about 0.0030. These structures have a 1V:2.5H sloping crest, are 15.5-ft-high with a 5-ft-high stilling basin, so the vertical drop between crest and downstream invert is 10.5 ft. The length of the stilling basin is a function of the downstream water-surface elevation. The channel base width is 800 ft and the flow is constricted at the drop structures' crest to 500 ft. The flood control project is designed for the SPF peak of 98,000 cfs. One of the objectives of this project was to maintain groundwater recharge in the natural channel. In the project design, consideration was also given to a trapezoidal reinforced-concrete channel with off-channel spreading basins. The cost of the natural channel bed and drop structure design was substantially less than the paved channel. A section through a typical drop is shown below.

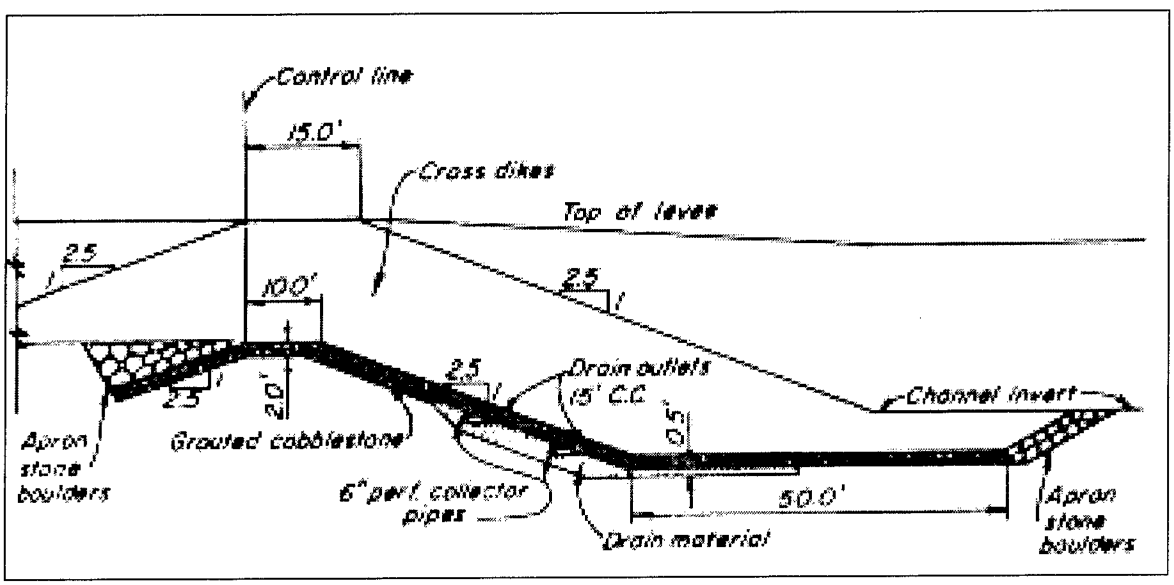

Figure 6. Section through drop structure

Hydraulic model studies were conducted at U.S. Army Engineer Research and Development Center in 1983-87 to evaluate drop structure designs for the Santa Ana River in Orange County, California (George, Pickering, and Turner 1994). A recommended design was developed for a grouted rock drop structure. This structure also had a 10.0-ft drop between the crest and downstream invert. Satisfactory hydraulic performance was demonstrated for unit discharges between 50 and 250 cfs/ft. Although the grouted stone structure was determined to perform satisfactorily, a reinforced concrete structure was finally chosen for construction by the U.S. Army Engineer District, Los Angeles. A section through this grouted rock structure is show below.

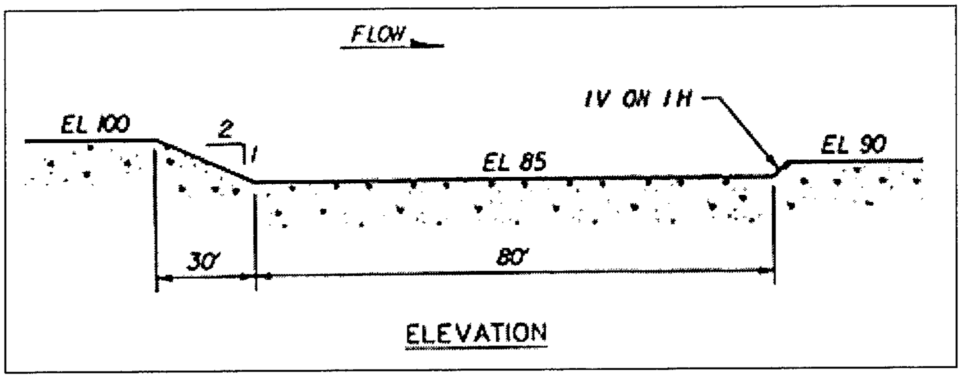

Figure 7. Section through grouted rock structure

Evaluation of degradation potential

A better understanding of the existing causes of degradation and the potential for additional degradation, especially during the design flood, can be obtained by conducting field surveys and using a numerical sedimentation model. To accomplish this objective a survey of the existing channel thalweg should be conducted and compared to pre-project and/or as-built surveys. In addition, natural or constructed grade control structures and local scour locations should be identified during the survey. Maintenance activities that included sediment removal, disruption of the armor layer, or channel reshaping should be documented. The HEC-6 numerical sedimentation model could then be used to identify general degradation trends, degradation potential during the design flood, and locations where severe scour due to constriction might be expected. The numerical model could also be used to evaluate a threshold channel design.

There are a number of uncertainties associated with using HEC-6 to analyze a stream such as Iao Stream. Sediment transport processes are not well known in cobble-boulder streams. No sediment transport function has been developed for use on streams with flow near critical depth or with bed material exceeding 32 mm. At very high discharges the flow may not even behave as a Newtonian fluid. A one-dimensional sediment transport model cannot predict local scour potential due to channel bends or local impingement. The contribution of sediment from bank erosion cannot be calculated by the model and must be estimated from other methods.

It is important to recognize the uncertainties associated with using HEC-6. However, the limitations of the HEC-6 analysis are not so much due to numerical model limitations as they are due to state-of-knowledge limitations. The knowledge gap, therefore, applies to any analytical analysis of Iao Stream. The advantage in using a numerical sedimentation model is that both continuity of sediment transport from one cross section to the next and continuity of sediment in the streambed can be accounted for over a long-term historical hydrograph. A numerical model is the only practical way to evaluate armoring and hydraulic sorting over the course of time. In Iao Stream, the model should not be relied on to predict exact quantities of aggradation and degradation; rather the model should be used as an analytical tool to evaluate trends that develop as a consequence of various processes or changes to the channel geometry.

HEC-6 has been used as an analytical tool to evaluate sediment processes on several coarse-bed streams. These include the Truckee River in Reno, Nevada (Hall and Thomas 1993), Santa Paula Creek in California (U.S. Army Engineer District, Los Angeles 1995), and Mission Creek in California (Copeland, McVan and Stonestreet 2000).

References

Copeland, Ronald R., McVan, Darla C., and Stonestreet, Scott E. (2000). "Sedimentation study and flume investigation, Mission Creek, Santa Barbara California, Corte Madera Creek, Marin County California," Technical Report ERDC/CHL SR-00-05, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

George, John F., Pickering, Glenn A., and Turner, Herman O. (1994). "General design for replacement of or modifications to the Lower Santa Ana River Drop Structures, Orange County, California, hydraulic model investigation," Technical Report HL-94-4, U.S. Army Engineer, Waterways Experiment Station, Vicksburg, MS.

Hall, Brad R., and Thomas, William A. (1993). "Truckee River sedimentation study," Technical Report HL-93-13, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

U.S. Army Engineer District, Los Angeles (1995). "Santa Paula Creek general re-evaluation report, Appendix A, engineering analyses," Los Angeles, CA. (Reference: Dave Cozakos)

J. Craig Fischenich
Research Hydraulic Engineer
Environmental Laboratory
U.S. Army Engineer Research and Development Center

The Honolulu District, Maui County, and others involved with the Iao Flood Control Project are to be complimented for their initiative and efforts. I was most impressed with the briefing package prepared for the Committee on Channel Stabilization (CCS) and with the competence of those involved from the above organizations.

I am in general agreement with the recommendations of the CCS during the wrap-up meeting. In my tenure with the CCS, I can't recall a project with more consensus – so these recommendations (summarized in the Committee report) should provide good general guidelines for the formulation of project improvements.

I'll restrict my comments to a few cautionary notes, suggestions, and recommendations that might not otherwise be captured in the Committee report and general recommendations. Organizationally, I've divided my comments into three sections: evaluation of existing conditions, project improvements, and recommendations for long-term management.

Evaluation of existing conditions

Assessing stream processes on the basis of a single site visit is difficult, and the District should consider this when contemplating the CCS recommendations. However, I think the evidence supports the assertions of the CCS during the meetings that degradation is the primary culprit in destabilizing the system. The causes of this degradation are numerous, and cannot be directly addressed without compromising the performance of the project for its authorized purpose. Full armoring of the banks and the bed are required to prevent further degradation and the compromise of the project.

Though the approach utilized by the District for evaluating levee failure was appropriate for the economic assessment, I would expect the levee with the vertical bank near Sta 40+00 to be the first to fail given the existing conditions. Unfortunately, I didn't mark my maps and don't recall if this was the upper portion of Levee A or the downstream end of Levee B. Either way, this reach is in critical condition and in immediate need of repair.

Given the dimensions of the sediment detention basin and the landslide conditions for the region, I think the critical design case should assume that the basin will fill and the transport of large (>300mm) coarse material will occur through the project reach. For this reason and because of the corrosive conditions at the site, materials subject to failure from abrasion and corrosion should be avoided.

The geotechnical analyses suggest that rotational slips were considered the likely failure mechanism in the original levee stability evaluation. In light of the field evidence, I would recommend reassessing the levee stability assuming a wedge-type planar failure for the levee and bank slopes. The re-evaluation should incorporate conditions reflecting the lowered bed level of the stream.

Despite arguments to the contrary, I find it difficult to believe that the O'opu, Opae kala'ole, and Hihiwai can successfully negotiate the climb over the high drop structure near Market Street. Consideration should be given to modifying this structure with some relief that provides refuge for the organisms during the climb. This is a new one for me, so I don't have detailed recommendations. My mental picture of the "fix" is something akin to a practice wall for rock climbers – with numerous artificial hand and foot holds bolted to the face of the wall. As the flow over this drop during high flows is almost certainly in the nappe regime, these protrusions will not affect the drop structure performance. Alternatively, the structure could be modified to include a series of steps and function in the skimming regime, but I doubt the increased costs would be justified.

Project improvements

The first order of business must be the restoration of the levee integrity. This should be done within the context of the overall improvement plan, but damaged areas must be repaired quickly. I would suggest immediate repairs to the levee section near Sta 39+00 or 40+00.

The general recommendation of the Committee is to provide a continuously armored channel throughout the project reach to prevent failure from erosion and streambed degradation. I agree with this assertion but, because of the environmental and aesthetic objectives of the project, think the channel should incorporate a low-flow section to accommodate aquatic organisms and that the bank treatments should be as natural in appearance as possible. The low-flow channel should be sized for the flows anticipated once the cane irrigation is halted and the diversions no longer active. The trick to this design is to find a means to maintain the stability of the low-flow channel while concurrently providing adequate substrate for the organisms and for vegetation establishment. Two options come to mind: use native bed material and develop a means to retain the material or use material large enough to be stable under the full range of flow conditions. Because of the abrasive and corrosive conditions in the channel, conventional retention materials (wire, geosynthetics, etc.) will probably not perform adequately, so I would recommend using the second option. Derrick-type stone averaging about 4 ft in thickness placed 3 ft-wide across the channel bed and overtopped about 2 ft on either side with the roller compacted concrete (RCC) or otherwise tied into the bank stabilization measures should meet the project objectives. The interstices could be filled with crushed stone to provide a bedding substrate for vegetation (discussed further below). Cutoffs (grouted sections perpendicular to the flow extending across the entire channel at and below the bed elevation) every 200 ft would enhance stability of the derrick stone and would limit any failures to discrete sections.

The stabilizing benefits of vegetation can be a strong inducement for their incorporation into flood-control projects. Leaves and stems of plants intercept rainfall and reduce surface erosion both from runoff and from overbank flooding. Vegetation, primarily woody plants, also helps to prevent mass movement, particularly shallow sliding-in slopes. The roots of many woody species reinforce soil particles and substantially improve the tensile strength of the underlying soil mass. A root-reinforced soil behaves as a composite material in which elastic fibers of relatively high tensile strength (roots) are embedded in a matrix of relatively plastic soil. Tractive forces between the roots and the soil add shear strength to the composite. Vertical root systems can also penetrate through the soil mantle into firmer strata below, thus anchoring the soil to the slope and increasing resistance to sliding. Roots also modify the soil moisture content of the soil, thus increasing slope stability and can eliminate geotechnical failures related to high pore water pressure. Compared with unvegetated streambanks, soils in vegetated banks are drier and better drained. Anchored and embedded stems can act as buttress piles or arch abutments in a slope, counteracting shear stresses and preventing soil sliding around and between vegetation components. The weight or surcharge of large trees exerts a stress component perpendicular to the slope that tends to increase resistance to sliding. The downslope component of stress imparted from surcharge can also have a destabilizing influence on the slope, however, and this must be weighed against its benefits. Likewise, there are other destabilizing influences of vegetation. Of generally minor concern is the alleged tendency of roots to invade cracks, fissures, and channels in a soil or rock mass and thereby cause local instability by wedging or prying action. Of greater concern is the destabilizing influence from turning moments exerted on the soil mass as a result of strong winds or flowing water moving across the vegetation. This can become particularly troublesome when the turning forces are sufficient to uproot the vegetation and expose the underlying soil to further erosion. Thus, the affect of vegetation on soil stability is the sum of the root reinforcement, soil moisture modification, and buttressing benefits minus the root wedging and overturning drawbacks, with consideration for both the stress components of surcharge.

For the Iao Project, I would contemplate utilizing herbaceous vegetation on the upper slopes of the banks and levees, and would permit vegetation establishment in the bed of the channel along the low-flow section. The upper slope vegetation should be supported during the development period by an erosion control mat (ECM). ECMs include the wide variety of natural and synthetic fabrics, meshes and grids used to prevent soil erosion and reinforce vegetation. They fill a void between the erosion resistance of bare soil and that provided by a hard armor. If properly installed, and under the right circumstances, these materials can withstand relatively severe flow conditions. Many engineers have adopted the design procedures presented by the Federal Highway Administration (FHWA) in the most recent HEC-15 Manual (1988). This design methodology utilizes maximum shear stress calculations in determining the suitability of various lining materials. An approach to evaluate the shear stress distribution along the banks is presented later in this section. You'll want to find the breakpoint where the RCC (or other stabilization material) is no longer needed and the vegetation/ECM combination is adequate to stabilize the banks.

Ideally, the low-flow channel should include native vegetation primarily from the sedge (*Cyperaceae*) family including *Scirpus, Eleocharis, Cyperus* and *Fimbristylis*. However, I think you will be hard-pressed to prevent the invasion of *Arundo donax* unless you get a good stand of vegetation established in the interstices of the derrick stone. Controlling the *Arundo* is discussed further in the section on maintenance.

Though we didn't address it during the Committee meetings, I think the concrete-lined lower reach should be extended upstream just beyond the Heiau (to approximately Sta 43+00). The reach adjacent to the Heiau is very constricted and full armoring with concrete is warranted. The channel should incorporate features to capture left overbank flow in a manner in which the stability of either the channel or the floodplain is not compromised. From that point, the section can transition into the "design section" that incorporates the other features addressed in this report.

One option contemplated for stabilizing the banks is the use of hard armor materials (such as RCC) on the lower and middle portions of the banks in conjunction with bioengineering techniques on the upper slopes. Biostabilization techniques to reinforce slopes and streambanks, popular in the 1930s in the U.S., have experienced resurgence here and in Southeast Asia in recent years. They have been used for centuries in Europe. Soil bioengineering is the use of live and dead plant materials, in combination with natural and synthetic support materials, for slope stabilization, erosion reduction, and vegetative establishment. Soil bioengineering techniques can be useful in meeting multi-objective erosion control projects, such as on the Iao, because some techniques can be used to concurrently control erosion and provide environmental benefits (habitat and aesthetics, for example).

Bioengineering techniques best suited to stabilizing the upper banks on the Iao are those that either promote the development of woody vegetation growth with extensive and deep root systems, or employ woody or herbaceous vegetation with considerable draught tolerance. Techniques that may prove successful in meeting the first objective include brush mattresses, wattling, brush layering, and perhaps posts, whereas native grasses seeded under an erosion control matting (ECM) are probably the best bet for meeting the second objective.

a. Brush mattresses. A brush mattress, sometimes called brush matting or a brush barrier, is a combination of a thick layer (mattress) of interlaced live willow switches or branches and wattling. Both are held in place by wire and stakes. The branches in the mattress are usually about 2 to 3 years old, sometimes older, and 5 to 10 ft long. Basal ends are usually not more than about 1.5 in. in diameter. They are placed perpendicular to the bank with their basal ends inserted into a trench at the bottom of the slope in the splash zone, just above any toe protection such as a rock toe. The branches are cut from live willow plants and kept moist until planting. The willow branches will sprout after planting, but care should be taken to obtain and plant them in the dormant period, either in the late fall after bud set or in the winter or early spring before bud break. A compacted layer of branches 4 to 6 in.-thick is used and is held in place by either woven wire or tie-wire. Wedge-shaped construction stakes (2 by 4 by 24 in. to 2 by 4 by 36 in., diagonal cut) are used to hold the wire in place. A gauge and type suitable for tie-wire is No. 9 or 10 galvanized annealed. It is run perpendicular to the branches and also diagonally from stake to stake and usually tied with a clove hitch. If woven wire is used, it should be a strong welded wire (2 by 4 in. mesh). The wedged-shape stakes are driven firmly through the wire as it is stretched over the mattress to hold it in place. The wedge of the stake compresses the wire to hold the brush down.

b. *Wattling.* Wattling is a sausage-shaped bundle of live, shrubby material made from species that root very quickly from the stem, such as willow and some species of dogwood and alder. These bundles are laid over the basal ends of the brush mattress material that was placed in the ditch and staked. Wattling bundles may vary in length, depending on materials available. Bundles taper at the ends, achieved by alternately (randomly) placing each stem so that about one-half of the basal ends are at each end of the bundle. When compressed firmly and tied, each bundle is about 15 to 20 cm in diameter in the middle. Bundles should be tied with either hemp binder twine or can be fastened and compressed by wrapping "pigtails" around the bundle. "Pigtails" are commonly used to fasten rebar together. If tied with binder twine, a minimum of two wraps should be used in combination with a non-slipping knot, such as a square knot. Tying of bundles should be done on about 38-cm centers. Wattling bundles should be staked firmly in place with vertical stakes on the downhill side of the wattling not more than 90 cm on center and with the wedge of the stake pointing upslope. Also, stakes should be installed through the bundles at about the same distance, but slightly offset and turned around so their wedge points downslope. In this way, the wedge stakes, in tandem, very firmly compress the wattling. Where bundles overlap, an additional pair of stakes should be used at the midpoint of the overlap. The overlap should be staked with one pair of stakes through the ends of both bundles while on the inside of the end tie of each bundle.

c. *Brush layering.* Brush layering, also called branch layering or branch packing, is used in the splash zone, but only in association with a hard toe, such as rock riprap, in the toe zone. It can also be used in the bank zone as discussed later. This is a treatment where live brush that quickly sprout, such as willow or dogwood species, are used in trenches. Trenches are dug 2 to 6 ft into the slope, on contour, sloping downward from the face of the bank 10 to 20 deg below horizontal. Live branches are placed in the trench with their basal ends pointed inward and no more than 6 in. or more than 18 in. of the tips extending beyond the fill face. Branches should be arranged in a crisscross fashion. Brush layers should be at least 4 in. thick and should be covered with soil immediately following placement and the soil compacted firmly.

d. *Seeding and ECM.* One of the more common types of ECM used in restoration designs are the temporary mats and fabrics intended to provide erosion protection only until vegetation can become well established and assume this function. There are two distinct categories of temporary ECMs: photodegradable and biodegradable. Within those two categories is a wide range of products made from such natural fibers as straw, coconut (coir) fiber, wood excelsior, flax, and jute. The different fibers provide significantly different characteristics, features, and benefits. These ECMs are entirely degradable, meaning that biological organisms break down the fibers over time (biodegradable), or sunlight accomplishes the same objective (photodegradable). The coir-based biodegradable mattings are probably the best bet for the Iao Project, and it should be placed over a seedbed that includes native grasses well-adapted to the site conditions. Enlist a local botanist to help develop the seed mix and discuss maintenance requirements (the objective is to be maintenance free, including mowing).

Recommendations for long term management

In addition to formulating plans to address immediate levee integrity, the District should develop a long-term management plan for the Iao Project. Based on my observations and the information provided, I believe the County has done an admirable job to date in maintaining the project. I would anticipate the County to continue its rigorous maintenance program, but think it is incumbent upon the District to minimize necessary maintenance. My two biggest maintenance concerns are the sediment detention basin and invasive vegetation.

Given the nature of the landslide processes and weather patterns on the islands, I believe that a sequence of high flow events over a short time frame, coupled with a major landslide in the watershed is a real possibility. The volume of material delivered from a significant landslide would be more than sufficient to fill the existing debris basin. Should another high-flow event follow prior to the removal of the debris, significant damage could occur to the project reach. I understand that the County no longer has the equipment necessary to undertake a major sediment removal project and would need to contract for these services. The turnaround time for the development, issuance and execution of such a contract may be too long to preclude the damages described above. I would encourage the County to acquire the necessary heavy equipment and maintain a readiness to rapidly deploy and remove material following any significant sediment delivery to the basin.

Healthy riparian vegetation tends to stabilize streambanks; provides shade that prevents excessive water temperature fluctuations; performs a vital role in nutrient cycling and water quality; improves the aesthetic and recreational benefits that can be derived from a project; and is immensely productive as wildlife habitat. Vegetation should be permitted on the upper bank slopes and along the low-flow channel of the project to obtain some of these benefits. Not all species or assemblages of vegetation provide these benefits, however, and there is a tradeoff in flow conveyance.

Hydraulic impacts of vegetation are a function of the flow conditions, the vegetation density, the flow depth relative to the vegetation type, and the species composition of the vegetation. In general, grasses and pliable herbaceous vegetation offer less resistance than stiff, woody vegetation. Resistance increases with increasing flow depth until vegetation is overtopped, after which it decreases with increasing flow depth – so short vegetation is preferable to tall vegetation from a conveyance perspective. Two Technical Notes available for download from the ERDC Environmental Laboratory home page offer guidance to evaluate impacts associated with herbaceous and woody vegetation. These include (a) Fischenich, J. C. (1999). "Resistance due to vegetation," TN EMRRP SR-7, USACE ERDC, Environmental Laboratory, Vicksburg, MS, and (b) Fischenich, J. C., and Dudley, S. (1999). "Determining drag coefficients and area for vegetation," TN EMRRP SR-8, USACE ERDC, Environmental Laboratory, Vicksburg, MS. The n-VR method is recommended for the herbaceous vegetation, and hydraulic impacts associated with woody vegetation can be determined by computing a C_dVeg_d value from calibrated conditions for the design event in the overbank areas using:

$$C_dVeg_d = \frac{2g\,n^2}{R^{4/3}k_n^2}$$

where

C_dVeg_d = the bulk drag-density term for the vegetation

g = gravity constant

n = Manning's resistance coefficient for calibrated flow

R = hydraulic radius for calibrated flow

K_n = unit conversion for Manning's equation (1 for SI, 1.486 for English)

The above equation can be rearranged to evaluate resistance for other overbank flow conditions by changing the hydraulic radius, or can be used to assess changes in flow conditions attributable to vegetation thinning (reduced density). The equation assumes the woody vegetation is not completely overtopped. More rigorous techniques and more complicated algorithms are required if the vegetation is overtopped. Note that when vegetation occupies only a portion of the flow area, the Alpha method in HEC-2 will overestimate conveyance because losses associated with the open channel-vegetation interface are not accounted. This shouldn't present a problem when using C_dVeg_d values estimated from calibrated n values. If other techniques are used to determine n values, increase estimated n values by 10 to 15 percent to account for losses at the interface.

Control of cane (*Arundo donax)* may become a problem in the channel. *Arundo* is a tall erect, perennial, cane-like or reed-like grass, 2 to 8-m-high. It is one of the largest of the herbaceous grasses. The creeping rootstocks form compact masses with tough fibrous roots that penetrate deep into the soil. They are hollow, with walls 2-7 mm-thick, and divided by partitions at the nodes. The outer tissue of the stem is of a siliceous nature, very hard and brittle with a smooth glossy surface that turns pale golden yellow when the culm is fully mature. The leaf sheaths are tightly wrapped around the stem and often persist long after the blades have fallen. *Arundo donax* is often considered indigenous to the Mediterranean Basin or to warmer regions of the Old World, but it is apparently an ancient introduction into Europe from the Indian subcontinent. *Arundo* is hypothesized to displace native plants and associated wildlife species as a consequence of the massive stands it forms (Bell 1994); the mechanism of competition with native species is not established. It clearly becomes a dominant component of the flora and is regarded as a major nuisance species in the Southwest U.S. Unlike native riparian plants, *Arundo* provides little shading to the in-stream habitat, leading to increased water temperatures and reduced habitat quality for aquatic wildlife (Hoshovsky 1988).

It appears that plants in North America do not produce viable seed, and seedlings are not observed in the field. Population expansion here occurs through vegetative reproduction, either from underground rhizome extension of a colony or from plant fragments carried downstream, primarily during floods, to become rooted and form new clones (Else 1996). New shoots arise from rhizomes in nearly any season, but are most common during spring. Growth likewise occurs in all seasons, but is highly sensitive to temperature and moisture (Perdue 1958). During warm months with ample water *Arundo* culms are reported to attain growth rates of 0.7 m per week or about 4 in. per day, putting it among the fastest growing terrestrial plants. Biomass production has been estimated at 8.3 tons dry weight per acre (Perdue 1958). Young stems rapidly achieve the diameter of mature canes with subsequent growth involving thickening of the walls (Perdue 1958).

Thick stands of *Arundo* will cause a considerable loss of conveyance for intermediate flow events, but probably won't have much of an effect stages for the SPF. The best way to keep it out of the channel is to get a good vegetation cover of desirable species established. Control measures that should be considered if the *Arundo* growth becomes excessive in the channel include mechanical removal, application of herbicides, and burning.

a. *Mechanical removal.* Minor infestations can be eradicated by manual methods. Hand pulling works with new plants less than 2 m in height, but care must be taken that all rhizome material is removed (Hoshovsky 1988). This may be most effective in loose soils, and after rains have made the substrate workable. Plants can be dug using hand tools (pickax, mattock and shovel), especially in combination with cutting of stems near the base with pruning shears, machete, or chain saw. Stems and roots should be removed or burned on-site to avoid re-rooting, or a chipper can be used to reduce material although clogging by the fibrous material makes chipping difficult. For larger infestations on accessible terrain, heavier tools (rotary brush-cutter, chain saw or tractor-mounted mower) may facilitate biomass reduction followed by rhizome removal (or chemical treatment). Such methods may be of limited use on complex or sensitive terrain, or on steeply-sloped banks, and may interfere with re-establishment of native plants and animals (Hoshovsky 1988). Mechanical eradication is extremely difficult, even with use of a backhoe, as rhizomes buried under 1 to 3 m of alluvium readily resprout (Else 1996). Removal of all such material is infeasible, especially where extensive soil disturbance would be disruptive.

b. *Chemical control.* In many, if not all, situations it may be necessary to use chemical methods to achieve eradication, usually in combination with mechanical removal. The most common herbicidal treatment against *Arundo* is glyphosate, primarily in the form of Rodeo® which is approved for use in wetlands (Round-Up® can be used away from water). Because glyphosate is a broad-spectrum herbicide, care should be taken to avoid application or drift onto desirable vegetation. The standard treatment is a foliar spray application of 1.5 percent by volume glyphosate with a 0.5 percent v/v non-ionic surfactant (Monsanto 1992). Most effective application is post-flowering and pre-dormancy, usually late July to early October when plants are translocating nutrients into root and rhizomes (TNC 1996). Foliar uptake and kill may be achieved by spray application during active growth periods, primarily late spring through early fall (Monsanto 1992). Small patches can be treated from the ground using backpack or towed sprayers, and major infestations have been aerially sprayed using helicopters.

Direct treatment to cut culms can reduce herbicide costs and avoid drift onto desirable plants, with fair results year-round and best kill in fall (Else et al. 1996). Concentrated glyphosate solution (50 to 100 percent Rodeo or RoundUp, or 27 – 54 percent glyphosate) is applied to stems, cut within 5-10 cm (2-4 in.) of the substrate, by painting with a cloth-covered wand or a sponge, or spraying with a hand "mister." It may be helpful to add a dye or food coloring to the solution to indicate treated material. Solution must be applied immediately following cutting because translocation ceases within minutes of cutting; a five-minute maximum interval is suggested (TNC 1996). New growth is sensitive to herbicides, so a common alternative is to cut or mow a patch and allow regeneration, returning later (3 weeks to 3 months) to treat new growth when 1-2 m-tall by foliar spraying of glyphosate. Promoting regrowth causes nutrients to be drawn from the roots, potentially reducing the translocation of glyphosate to the roots (TNC 1996). With all methods followup assessment and treatment should be conducted, and some professional applicators suggest 6 return spot treatments over 6 months. Other chemical control methods have been tested including Dowpon-C, 2,2 DPA, paraquat, and triclopyr compounds (e.g., Dow Chemical's Garlon)(Arnold and Warren 1966; Horng and Leu 1979; Franklin 1996), but are not currently recommended due to labeling restrictions or lower efficacy.

c. Prescribed *burning.* Some success has been obtained recently by burning *Arundo* stands, then flooding and ponding the stand for several months. This will probably not be a viable option for the Iao project, however. In most circumstances burning of live or chemically-treated material should not be attempted, as it cannot kill the underground rhizomes and probably favors giant reed regeneration over native riparian species. Burning in place is problematic because of possibility of damage to beneficial species and the difficulties of promoting fire through patchily-distributed stands. There may be some cases where burning attached material can be done, but only if other means of reducing biomass cannot be carried out. Cut material is often burned on-site, subject to local fire regulations because of the difficulty and expense involved in collecting and removing or chipping all material.

References

Arnold, W. J., and Warren L. E. (1996). *Dowpon C. Grass Killer – a new product for controlling perennial grasses such as Johnson grass and Bermuda grass.* Down to Earth 21, 14-16.

Bell, G. (1994). "Biology and growth habits of giant reed (*Arundo donax*)," N.E. Jackson et al. *Arundo donax* workshop, 1-6.

Else, J. A. (1996). "Post-flood establishment of native woody species and an exotic, *Arundo donax*, in a southern California riparian system," M. S. thesis, San Diego State University.

Else, J. A., Lawson, D., and Vartanian, V. (1996). "Removal of *Arundo donax* on the Santa Margarita River: effectiveness of different removal treatments and recovery of native species." Abstract, California Exotic Pest Plant Council Annual Symposium, San Diego.

FHWA. (1988). "Design of roadside channels with flexible linings," Hydrologic Engineering Circular 15, Federal Highway Administration, Washington, DC.

Fischenich, J. C. (1999). "Resistance due to vegetation," Technical Note EMRRP SR-7, U.S. Army Engineer Research and Development Center, Environmental Laboratory, Vicksburg, MS.

Fischenich, J. C., and Dudley, S. (1999). "Determining drag coefficients and area for vegetation," Technical Note EMRRP SR-8, U.S. Armey Engineer Research and Development Center, Environmental Laboratory, Vicksburg, MS.

Franklin, B. B. (1996). "Eradication/control of the exotic pest plants tamarisk and *Arundo* in the Santa Ynez River drainage," USDA-FS-PSW.

Horng, L. C., and Leu, L. S. (1979). "Control of five upland perennial weeds with herbicides." *Proceedings 7th Asian-Pacific Weed Science Conference,* 165-167.

Hoshovsky, M. (1988). *Element stewardship abstract: Arundo donax.* The Nature Conservancy, San Francisco, CA.

Monsanto Corp. (1992). *Native habitat restoration: Controlling Arundo Donax.* Monsanto Co. Application Guide Circular No. 170-92-06.

Perdue, R. E. (1958). "*Arundo donax* - source of musical reeds and industrial cellulose." *Econ. Bot.* 12, 368-404.

The Nature Conservancy. (1996). "Control and management of giant reed (*Arundo donax*) and saltcedar (tamarix spp.) in waters of the United States and wetlands." Report by The Nature Conservancy, Southern California Projects Office, U.S. Army Engineer District, Los Angeles.

Meg Jonas
Hydraulic Engineer
U.S. Army Engineer District, Baltimore

Operation and maintenance of flood control project

Maui County has done an outstanding job of maintaining the project to date. However, it seems that lack of adequate equipment may hamper their ability to maintain the project in the future. The periodic removal of sediment and debris is critical to the proper functioning of the project. I would recommend that the County take whatever steps are necessary to insure that the project can continue to be maintained.

Impacts of filling debris basin

The likelihood that a large flood (either a single event or a series of events) might overload the debris basin should be assessed. If it is likely that the debris basin might be filled during a flood event, the downstream channel should be sized to handle sediment and debris.

Review of top of protection

The existing top of protection should be re-surveyed to make sure no settlement has occurred since construction. The computed water surface profile should be checked carefully, for both existing and proposed conditions. Since flow in a natural channel does not usually go below critical depth, the occurrence of supercritical flow for any extended reach in the model should be reviewed to make sure it is legitimate.

Flood warning system

Since the project in its current condition might have significant problems during a large flood, a flood warning system could prove beneficial (particularly as an intermediate measure before the flood control channel is rehabilitated).

Monitoring of performance of environmental channel

If the channel proposed by the Committee is constructed, funding should be included for monitoring to see if it does allow passage for the target species.

Jim Lencioni

Senior Hydraulic Engineer
U.S. Army Engineer District, Seattle

Site inspection and discussion

The concrete lined channel at the downstream end of the project has a grouted boulder bed which appears to be performing quite well even considering that it has not been exposed to conditions near those with the project design flood. This type of construction appears to be a reasonable approach in this climate where freeze/thaw conditions do not exist. The POH geotechnical staff evidently has voiced reservations regarding use of grouted stones when exposed to velocities much in excess of 20 fps. However, I would not be overly concerned with performance of this type of material even if exposed to significantly higher velocities provided that the boulders are imbedded to at least two-thirds of their depth. ETL 1110-2-334 dated 21 Aug 1992 "Design and construction of grouted riprap" contains guidance which should be reviewed by POH regarding detailed design of this type of treatment.

Representatives of the local sponsor indicated that 20,000 to 40,000 cu yd of material is removed annually from the project's debris basin. If this is true, then it would appear that the debris basin is likely significantly undersized for the volume of debris which would be generated in a project design flood. This needs to be considered when designing the modifications to the project—some sediment will undoubtedly be moving through the channel during the design flood.

POH staff indicated that observed water surface elevations for the project do not exist. Therefore, development of accurate existing and with project modified condition water surface profiles for various discharges will be extremely difficult, especially through the natural channel portion of the channel. Subsequently, the existing level of protection afforded by the project is uncertain.

The CCS was shown an installation of shore protection utilizing very large, native stones which are in great supply on the island. POH staff had suggested using this stone in the modified project. It appears that this type of stone and construction could be an attractive and cost effective material for the Iao Stream Flood Control Project modification.

Conclusions and recommendations

The following are the conclusions and recommendations I offer as a result of my review, inspection and discussions held:

a. The existing condition of the natural channel portion of the project prevents the project from meeting its authorized level of protection. Due to the high energy levels existing in the Iao Stream, acceptable project performance cannot be achieved using a soft, naturally appearing channel design. Some form of hardened channel bed and bank armoring through the entire length of the present natural portion of the channel will be necessary to ensure that the project can provide reliable flood protection with the authorized SPF level of protection.

b. Two obvious problems exist in the natural channel: first, bed scour is threatening the integrity of the entire length of the right bank levee structure and second, portions of the levee embankment are not capable of withstanding the high velocities which will exist with high discharges. Both conditions must be addressed in the design to ensure that the project provides a reliable level of flood control protection.

c. Existing condition hydraulic computations in the natural reach developed using the HEC-RAS numerical model are very unstable and questionable. Some obvious reasons for this computational instability are significantly changing cross-section shape, unknown roughness (0.04 is probably low considering the amount of debris which exists at high flow), too much distance between cross sections, proximity to critical depth, etc. Although not necessary for design, the POH should attempt to get a better handle on existing profiles in order to adequately develop water surface profiles for existing condition damage assessment.

d. Levee failure assumptions for existing condition are needed to develop flood damage frequency data. The POH's approach to date has been to assume that the entire levee fails at 10-yr flood. Although this is a rather simplistic approach, it is probably as reasonable as one can do. Given the extreme bed instability which exists, it will be extremely difficult to estimate with any degree of certainty where, at what discharge and how much of the levee might fail. I believe that the entire levee reach is subject to essentially the same probability of failure. However, it might be possible to get a somewhat better estimate on failure threshold frequency by integrating water surface profiles with a detailed levee stability assessment by geotechnical engineers.

e. There are two general ways of designing to eliminate the type of scour existing in the project. First, one can take the approach of armoring the bed with material/methods which are capable of handling the imposed forces without displacement. The second method is to reduce the imposed forces to a degree that the existing bed material will not be displaced--i.e., reduce the stream gradient to a manageable degree by a series of grade control structures. I believe that the suggested composite bed design using a low flow channel composed of very large stones prevalent on the island with a grouted boulder treatment along the remainder of the bed is feasible. I would be conservative, however, in selection of the size of the low-flow channel stones as significantly large dynamic turbulence forces will probably be imposed on the stones with the high channel velocity which will exist. Extreme care needs to be taken in preparing the underlying bed and ensuring that there are minimal irregularities in boundary elevation introduced between individual stones as such irregularities will create large fluctuating uplift loads and turbulence. I would recommend POH do physical model studies of adequately scaled stones to arrive at the design stone size and limitations on irregularities. Possibly some of the investigations conducted a few years ago by Randy Oswalt on review of manufacturer's testing of proprietary erosion control mattresses and products would be pertinent. I would not place grout in the low-flow channel stones as that would defeat the free drainage capability it provides for the remainder of the channel bed. I recommend POH thoroughly review the guidance in ETL 1110-2-334 in design of this type of treatment. Grade control structures to reduce the stream gradient sufficiently to reduce velocities are probably feasible, but I suspect that the large number of structures (i.e., close spacing) required may be quite costly. I would suggest POH evaluate this alternative in sufficient detail to determine if it would be more cost-effective than the composite channel alternative. To develop the details of this alternative, the stable channel gradient and drop structure height must first be determined. The number of drop structures can then be determined by dividing the selected drop height by the difference between the natural channel slope and the stable slope. I would suggest that drop structure height not exceed 3 ft as considerable energy will need to be dissipated over each drop structure.

f. The high velocities which will exist in the modified channel will require a "hardened" type of protection on the entire length of levee. This protection could consist of grouted riprap or roller compacted concrete (RCC) to eliminate the "stark" appearance of a conventional concrete-lined surface. RCC would probably be the better choice as uneven settlement of the levee embankment will subject the grouted riprap blanket to forces which cannot be accommodated by it's rigid nature. The elevation of this type of protection on the right bank (leveed) is the elevation of the project design flood (SPF) water surface elevation plus the design uncertainty in the computed water surface. Above this elevation, smaller graded riprap or even vegetation may be adequate. An evaluation of the vertical velocity distribution using methods described in EM 1110-2-1601 can be used to determine the type of material which could be used near the top of the levee. The left (unleveed) bank will need to be protected using a "hardened" treatment to prevent bank erosion and subsequent introduction of sediment into the channel. Except in the channel reach in vicinity of the Halekii-Pihana heiau where bank protection should extend to the same height as on the levees, the height of the left bank protection does not need to extend as high as on the levees. This height could be arbitrarily selected at a certain discharge (frequency) or by some more complete evaluation of discharge frequency versus water surface elevation.

g. In designing the cross-section shape and size, some approach will be necessary to select channel roughness in the composite channel. POH should attempt to obtain observed water surface elevations at various discharges in the concrete lined portions of the project to assist in this endeavor. The existing U.S. Geological Survey stage gauges located in the channel downstream from the debris basin could be used for this purpose.

h. High velocities (likely on the order of 40 fps) will exist in the proposed composite channel. POH will need to develop a design that minimizes cross sectional and horizontal alignment irregularities to eliminate the introduction of water surface perturbations, waves, etc. Guidance on design of high velocity transitions is provided in EM 1110-2-1601. The channel slope and geometry needs to be selected to ensure that the Froude number in the channel is not in the range of 0.8 to 1.2 to ensure that the flow regime is not in the area of critical flow in order to ensure a stable water surface elevation.

i. Although not relevant to design of the modification, it may be advisable to attempt to develop a sediment budget in the existing system to compare the amount of inflowing debris to the debris basin with the channel scouring occurring in the natural channel downstream to assist in identifying the processes creating the existing instability.

Tom Pokrefke

Research Hydraulic Engineer
Coastal and Hydraulics Laboratory
U.S. Army Engineer Research and Development Center

Introduction

During the Committee on Channel Stabilization meeting on the subject project, a relatively detailed design was developed by the Committee using grouted rocks, roller-compacted concrete, and other materials. The design developed was aimed at providing a high velocity channel capable of carrying the SPF with velocities as high as 25 fps. The Committee members agreed virtually unanimously that the design was a reasonable replacement for the concrete-lined channel proposed by the Honolulu District (POH) which was not enthusiastically accepted by the local sponsor. The comments presented herein address the issue of planform and channel layout for the Committee-proposed design.

Stream Sinuosity

The following sinuosities were determined. Sinuosity being defined as:

Sinuosity = channel length/valley length

Reach of Iao Stream	Sinuosity
Sta 91+00 to 65+00	1.02
Sta 65+00 to 40+50	1.03
Sta 40+50 to 21+00	1.06
Sta 91+00 to 21+00 (entire project)	1.05

These values indicate that the present planform is relatively straight and does not vary significantly throughout the proposed project length. In the layout of the design, maintaining a constant sinuosity throughout the entire project length is not necessary. More important is maintaining a pool- (bendway) crossing-pool sequence that will be capable of carrying the SPF. It should be noted that the present planform has been developed with flows significantly lower (probably about 4,000 cfs) than the SPF flow of about 26,500 cfs. As discharge increases in a channel the flow will try to move downstream in a straighter path than for a lower flow condition. At the same time standing waves may be formed near critical flow conditions. Add to that the need to address bank heights in bends due to super elevation of the water surface in bendways, it can be seen that the design of the new channel will be complex. Since the Committee proposal involves a design which will virtually fix the planform, that designed planform needs to be keyed toward the SPF flow characteristics. According to Mr. Jim Pennaz, POH, the project will probably have a physical model study conducted to develop design parameters and evaluate project performance. The planform should be addressed prior to initiation of those studies.

Stream widths

The following channel dimensions were determined from data provided by the Honolulu District. It should be noted that the "stream base width" in the following tabulation are based on the stream delineation indicated with the 3 dot "contour" on the map. The "bank-to-bank width" is based on the HEC-RAS water-surface elevations (WSE) and the distance between those WSE contours on the maps. I believe that those computations were for the existing channel without the levee in place, but it was the only water-surface elevation information available at the time of the meeting. The "flow conditions" presented in the following tabulation are also from the HEC-RAS computations, which probably are not indicative of flow in the existing channel.

Location	Stream Base Width (ft)	Bank-to-Bank Width (ft)	Flow Conditions from HEC-RAS
D/S Outlet (Sta 91+00)	70	80	Subcritical
Sta 86+00 (near SCS Channel outlet)	40	50	Supercritical
U/S Cane Haul Rd Bridge (Sta 80+00)	30	45	Subcritical
U/S end of Levee D (Sta 76+00)	35	65	Supercritical
Middle of Levee D (Sta 71+00)	25	50	Supercritical
D/S end of Levee D (Sta 65+00)	25	35	Supercritical
Middle of Levee C (Sta 62+00)	60	105	Subcritical
Sta 60+00	150	210	Subcritical
Sta 55+00	60	130	Subcritical
U/S end of Levee B (Sta 49+00)	65	160	Supercritical
Levee B @ heiau sites (Sta 43+00)	60	105	Supercritical
U/S end of Levee A (Sta 36+00)	60	65	Supercritical
Middle of Levee A (Sta 28+00)	60	75	Supercritical
U/S of D/S Channel (Sta 21+00)	145	160	Supercritical

Therefore, in the existing channel the stream base width varies from 25 to 150 ft and the bank-to-bank width varies from 45 to 210 ft. The average stream width is about 65 ft and the average bank-to-bank width is about 95 ft. It should be noted that these widths have been developed with flows significantly less than the contained SPF and with modifications and maintenance activities in the reach.

For the proposed project with fixed bed and banks, the width should not be allowed to vary as much as it does in the existing channel. Some channel widening in the bendways will probably be required due to concentration of velocities in the outside (concave side) of the bends. Those bends will not be as efficient carrying discharge as the crossings; therefore, they are potential areas for change in flow conditions, i.e. supercritical to subcritical, and the waves that may occur then.

Stream slopes

Information in the provided notebook stated that the channel slope is 140 ft/mile (0.0265 ft/ft). The two topographic maps indicated that the existing channel invert elevation at Sta 91+00 is el 200 and el 27 ft at Sta 21+00. Those elevations produce an overall channel slope of 0.0247 ft/ft ((200-27)/(9100-2100)). A rough review of the spacing between contours crossing the stream on those two maps indicates that the four reaches from Sta 41+00 to 46+00, Sta 51+00 to 56+00, Sta 66+00 to 71+00, and Sta 86+00 to 91+00 have the steepest channel slopes. As the design of the channel progresses, the variations in slopes need to be incorporated into the overall project design. For example, the reach from Sta 41+00 to 46+00 is the portion of the channel adjacent to the heiau sites and in the general vicinity where the overbank flow will re-enter the channel during the SPF.

The significance of changes in channel slopes can be appreciated with past project performance. A review of the Plan and Profile drawings provided to the Committee indicated that from Sta 29+00 to 31+00, Sta 42+50 to 44+50, Sta 47+50 to 50+00, 57+50 to 59+50, Sta 61+00 to 63+00, and Sta 68+00 to 70+50 were six locations where the channel invert slope obviously increased relative to the invert slopes immediately upstream and downstream. These reaches of increased invert slope are virtually identical to reaches experiencing significant channel degradation in the past. While fixing the channel bed and banks will virtually eliminate channel degradation, the combination of varying channel slopes with varying channel widths fit into a desired planform could produce undesirable flow conditions.

Stream dynamics

Comparison of the reaches where the invert slopes increased in the original channel and the rough measurements of the slope I made from the topographic maps indicate that most of the reaches with higher original slopes have flattened. Thus the stream has been very dynamic in adjusting its slopes with the flows that have occurred on it. The channel degradation is the obvious indicator of those changes.

At the Committee meeting Jim Pennaz had a set of aerial photographs from 1996. A review of those photographs left me with the impression that the most sinuous portion of the stream, around Sta 50+00 to 60+00, had changed when compared to the two topographic maps and the conditions we saw during the site visit. If the planform changes are as dynamic as the impression left with me from the aerial photographs, the desired planform discussed above is even more critical. Fixing the bed and banks will control the channel migration during the lower and SPF flow events. The point here is that the conditions that exist today may be significantly different when the project design is installed.

Summary

I'm sure that Jim Pennaz would have wanted me to give him sinuosity, planform, and slope(s) for POH to use in their initial design. I wish I was able to do so, but I just can't provide him with that type of information. My purpose in providing these comments was to bring the issues up for POH to address as they work their way through the design. I believe that the physical model study will answer many, if not all, of their channel design parameters. It would be good during the design of that model to integrate some potential future channel adjustments to address some of the unknown or questionable parameters.

John Remus

Hydraulic Engineer
U.S. Army Engineer District, Omaha

Background

The Honolulu District has determined that the original project, constructed in 1981, has a design deficiency. The basic deficiency that concerned the Committee was an unstable channel that undermined the levees. The boulder streambed had degraded 3 to 8 ft in response to floods with discharges of

4,130 cfs or less. These floods are considerably less than the design flood of 26,500 cfs. The District has developed a design for a concrete channel at a cost of approximately $18.8 million. The current benefit/cost ratio is approximately 1.2.

Objective

The District wished the Committee to provide technically viable alternatives to the concrete channel. Also, the District asked the Committee to provide insight into possible levee failure areas.

Discussion

After viewing the site, the Committee brainstormed a number of possible solutions. I will not reiterate that discussion as I am in full support of the Committee's recommendations, as summarized by Ron Copeland. The following points were either not discussed or lightly discussed during the meeting.

a. For all design concepts, the construction quality control is very important, especially in the low flow channel.

b. Derrick stone should be placed so that the top edges of two consecutive stones are at the same elevations to prevent excessive uplift pressures and to prevent pools from forming.

c. If derrick stone is used, a 5-10 ft grouted section should be constructed every 100 ft or so to prevent the low flow channel from sustaining excessive damage during large flood events.

d. Both the District and the sponsor must realize that there will be considerable damage to any project when the SPF occurs. The debris basin will likely fill and some of the large boulders will be passed downstream. This large material may damage some of the concrete/grouted surfaces, and will likely settle out near and/or downstream of Waiehu Bridge. It is impèrative that the sponsor continues its outstanding maintenance program.

e. The District may want to consider a typical concrete channel in the vicinity of the heiau. This is a high pressure area with the constriction and the return flows from the left flood plain. An alternative may be to grout the entire section from the point that the flood plain flows return to downstream the heiau.

Mike Spoor
Engineering Geologist
U.S. Army Engineer District, Huntington

District staff, local interests, and consultants provided an exceptionally comprehensive review of the project, environmental concerns, and cultural considerations. This stream, and the project reach, evidence significant interrelated changes in land uses, causative processes, channel, bank and upslope stability and extent of flood damage reduction.

Hydraulic and environmental components have been evaluated by the District and by Committee members. Geotechnical processes were defined by what are typically considered as conservative strengths and loading assumptions and stability analysis. However, these assumptions and methods do not represent the complex erosion and failure features, which were observed during stream reconnaissance. We concur with District recommendations that an experienced professional geotechnical engineer should be retained. This expert would work with District civil and hydraulic engineers to design site and reach specific project treatments. This staff would be responsible for plans and specifications, conduct frequent inspections during construction to assure project functional integrity, prepare the operation and maintenance manual, and participate during initial post construction evaluations.

The Committee, District, and local sponsor are concerned about project sufficiency, impacts of frequently occurring high flow events, related damage and repairs, and greater than expected maintenance costs. Evaluations substantiate that referenced high flows have caused extensive bed degradation at and downstream from channel constrictions, along banks, and along embankments with grouted cobble and boulder slope and toe treatments. Bed degradation has resulted in slope undercutting and oversteepening with related berm, bank, and embankment failures. Bed degradation has increased extents of rapid recessional loading and slumping. Project reaches should be widened and excavated to stable geometries within inplace soils. Slopes and channels should be armored with concrete and grouted stone. Locations of overbank discharge and return flows should be stabilized. Environmental concerns could be partially addressed by construction of a derrick stone armored low flow channel. This channel would be planted with native herbaceous species. Replanting of upper slopes, along the left bank would limit boulder launching. Project maintenance would include debris and sediment basin cleanout and removal of cobbles and boulders from project channel reaches.

Geotechnical processes which contribute to bank, slope, and embankment instability, and failed soil erosion are complex and include erosional oversteepening and undercutting with related upslope failures during periods of rainfall and high flows. As the stream recedes from high stages more rapidly than bank and embankment soils can drain, recessional loading causes slumping and collapse. Seepage exit and internal erosion, or piping, cause cavity formation, and result in cantilevering, tension crack propagation and slabbing or block failures. Berms of failed soils and displaced cobbles and boulders shed secondary currents during moderate and high flows and cause additional erosion of inplace soils. Stream channel degradational processes increase vertical extents of rapid recession and groundwater gradients. Bed degradation outflanks project weephole systems with renewed piping occurring within undercut slopes. Collapsed grouted stone and concrete mantle toe of slope seeps and failure features.

Scott Stonestreet

Hydraulic Engineer
U.S. Army Engineer District, Sacramento

General comment

Overall, our meeting on Maui was a great trip for the Committee and gave the Committee members a good look at problems associated with high-energy steep streams. Specifically, the Iao Stream presents some unique problems and opportunities which I believe the Honolulu District has done a good job of trying to identify and quantify. The District should be commended for their understanding of the nature of the stability problems as well as an understanding of the social/political ramifications of concrete flood control channels in today's ecologically sensitive environment.

Key points

Hydraulic modeling. The District provided the output from an HEC-RAS run for the channel for the without-levee condition. A review of the data indicates that cross sections were spaced about every 200 ft. Jim Pennaz indicated that interpolated cross sections were used in the model to supplement the "physical" cross sections. My experience with steep streams, e.g., in the 2 to 4 percent range, indicates that stable hydraulic computations require cross section spacing as close as one every 50 ft or less. In addition to the recommendations in the CCS's main report, perhaps POH could use the WASURO or WS1D program to conduct the hydraulic computations for the channel design. WASURO was developed by Edward Chew of the Los Angeles District (LAD) in the 1980s and is available from LAD or ERDC. WS1D was developed by Scott Stonestreet and is available from him. WS1D uses standard step computations and can accommodate subcritical and supercritical flow, bridges, transitions, confluences, etc. WS1D has been used for the hydraulic design of the Los Angeles River and Rio Hondo channels as well as for the concrete-lined, supercritical channels designed for the Las Vegas flood control project.

Detailed hydraulic modeling of the left overbank may be required to determine the characteristics of the overbank flow and to determine the flowrate and specific locations where the flow will return to the channel. I would encourage the POH to consider using a two-dimensional model such as FSWMS, HIVEL2D, or FLO2D to model the left overbank. FSWMS is available from the Federal Highway Administration, HIVEL2D is available from ERDC, and

FLO2D is available from FLO Engineering, Inc. All of these models have shown that they can provide stable results in steep stream systems.

Debris yield. In general, regardless of what type of channel is used between the debris basin and the ocean, whenever the volume of the debris basin is exceeded, bed-material will be conveyed through the channel. I think that it is important for POH to get an estimate of what frequency flood will result in this condition. Perhaps a series of debris yield estimates for various n-year frequencies should be generated. These yields should be compared to the volume of the debris basin to identify the threshold frequency at which debris will exceed the basin and to determine the approximate volume (and potentially the concentration) of sediment passing on to downstream reaches of the channel. Given that the channel design focuses on the SPF, it is likely that any channel design should include the appropriate considerations for sediment transport of relatively large bed-load material.

Gradation analysis. Some discussion focused on the need for accurate bed-material gradations to support some sediment transport/stability analyses. I have successfully used grid-based photographic techniques to sample the surface layer of boulder and cobble streams. These samples were complimented by sampling the large bed material using a backhoe and large-scale mechanical sieves. Copies of a couple of journal articles documenting these techniques will be provided directly to Mr. James Pennaz.

Design considerations.

a. *Access ramps.* Be sure to point all vehicle access ramps downstream. Given the high velocity of the flow (and its corresponding velocity head), access ramps pointed upstream can cause flow to ride up and out of the channel (especially on the outside of channel bends).

b. *Channel chute.* Consider using a "channel chute" or steep section of the channel to accelerate flows through the constriction located near Sta 43+00. This chute could be combined with a transition reach and may provide sufficient momentum to the flow to maintain stable supercritical conditions.

c. *Maximum velocity for grouted stone.* During the meeting POH representatives indicated that the District was concerned about using grouted stone protection for flow velocities greater than 20 to 25 fps. I conducted a brief literature review and found that the Corps of Engineers doesn't appear to have hard guidance on this topic. It appears that existing guidance for concrete channels uses a threshold velocity of 40 fps as the point at which special construction techniques may be required. Additionally, it is at this velocity range that cavitation for flow on grouted stone may be the mechanism of failure. The best reference for construction of grouted stone appears to ETL 1110-2-334 "Design and construction of grouted riprap" (1992). A copy of this documentation will be provided directly to Mr. James Pennaz. Discussions with members of the Los Angeles District revealed that although guidance is lacking on this issue, potentially one approach to identify safe maximum velocities may be to query the Los Angeles District's records on the existing grouted stone channels located in that District. This would include reviewing the actual flood events which have occurred in the various grouted stone channels to determine maximum prototype velocities which have occurred since construction of the channels. The Los Angeles District reports that none of their grouted stone channels have failed from high velocity flow. I would recommend Mr. Dave Cozakos, Hydrology and Hydraulics Branch, as a point of contact in the Los Angeles District (213-452-3555).

d. *Sloping debris noses.* Consider using sloping debris noses on all bridge piers (ref. page B-20, Plate B-18, EM 1110-2-1601, 1994). In this channel, the pier noses would serve two functions: 1) minimize effective blockage caused by floating debris on the piers resulting in lower water surface elevations near bridges, and 2) the pier noses would act as a sacrificial element protecting the bridge piers from attack by the bed-material load.

e. *Increased roughness due to bed-load transport.* Given comment number 2 above, POH might want to include the effect of bed-load transport on the total hydraulic roughness of any proposed channel. In the early 1990s, the Los Angeles and Sacramento Districts engaged ERDC to conduct research on this issue during the design of concrete-lined, supercritical channels located in Santa Barbara and Corte Madera, CA. A copy of the documentation developed for the Los Angeles District will be provided directly to Mr. James Pennaz.

f. *Bend losses and transverse waves.* In addition to an increase in roughness due to bed load transport, the POH may want to quantify and include the effect of channel curvature on the hydraulic roughness for any proposed channel design. To that end, a copy of the paper "Bend losses and transverse waves" by Scott Stonestreet will be provided directly to Mr. James Pennaz.

Bank protection at Sta 43+00. During the field trip, one of the more spectacular sights included the eroding bank near Sta 43+00. It appears that the sideslope of the right levee (Levee B) has eroded by as much as about 15 to 20 ft (or more) horizontally. I would recommend that POH give this reach top priority since failure of the levee is imminent. I envision that the roller-compacted concrete (RCC) sideslope discussed for the channel alternative be constructed along the right bank as soon as possible along this critical reach (Figure 7). Future construction of the channel could be designed to tie into this "early-built" section as necessary. Perhaps, the RCC sideslope could be constructed a minimum of 10 ft below the existing thalweg to prevent undermining, at least for the next few years, while at the same time providing immediate bank protection along this reach. I recommend EM 1110-2-2006 "Roller-compacted concrete" (1992) as a reference for RCC design and placement.

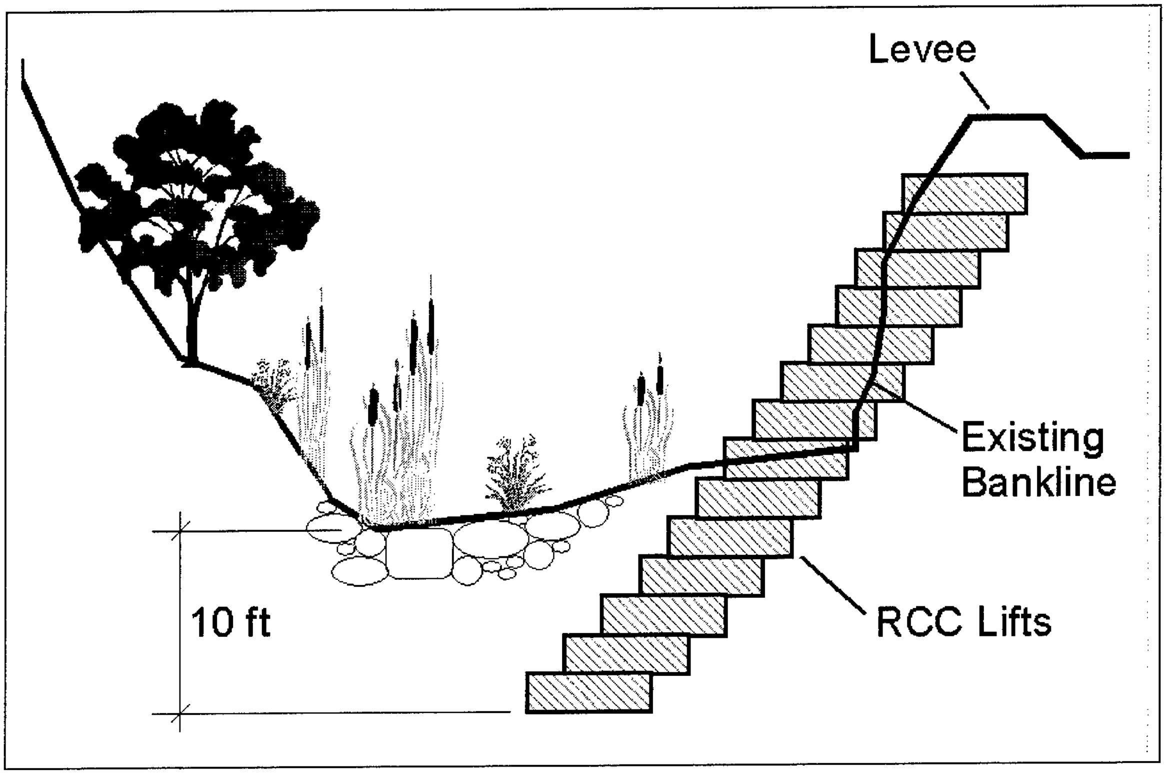

Figure 8. Bank protection alternative near Sta 43+00

Recap of information/guidance to be provided.

a. "Gravel size analysis from photographs," (1979).

b. "Surface sampling in gravel streams," (1993).

c. ETL 1110-2-334 "Design and construction of grouted riprap," (1992).

d. Paper on "Bedload roughness in supercritical flow," (1992).

e. Paper on "Bend losses and transverse waves," (1993).

Howard Whittington

Chief, Hydrology & Hydraulics Branch
U.S. Army Engineer District, Mobile

General

The support and preparation provided by the Honolulu District in general, and by Mr. James Pennaz and Mrs. Sharon Ishikawa in particular, was superb. I don't know of another Committee investigation where the preparation and service from the host district was better than here.

Additionally, the support and professionalism that was provided by the local sponsor (County of Maui) was also the best that I have seen. The local sponsor was committed, knowledgeable, and cooperative in trying to find the correct solutions to the problems associated with this stream. This sponsor should be commended for the terrific job accomplished in maintaining the project. We were distressed to learn, however, that they no longer have access to a D-8 or larger dozer that can be used to perform the periodic maintenance. Unless this can be rectified, I fear that maintenance of the channel will deteriorate from the excellent level that is now evident.

Project

Constructed in 1981, the project consists of a high velocity channel to carry flood flows coming out of the West Maui Mountains through a commercial and residential area in the town of Wailuku on the Island of Maui. The steep drainage basin is only about 10 square miles in area, but has a SPF design peak discharge of about 27,000 CFS. To date the channel has prevented approximately $18.9 million in damages, but the very high velocities are beginning to erode and reduce the stability of the channel in spite of the excellent maintenance work done by the local sponsor.

The problem is that, as designed, the channel cannot stand up to the high velocity flow unless it is hardened to resist the high scour potential that exists during flood discharges. To illustrate this, while the channel has degraded significantly, no flood as large as a 20-year event has yet occurred. Peak discharges on the stream have only reached 4,130 cfs, during the April 9, 1989, storm.

The plan of the Honolulu District to stabilize the channel is to pave the channel with concrete. This has met with resistance from the local sponsor and residents of Wailuku, and the Committee on Channel Stabilization was asked to assess the project and recommend solutions.

Results and recommendations

While in Maui, the Committee definitively discussed and summarized the objectives, constraints, active processes, recommended evaluations, design objectives, and recommendations. I am in full agreement with these analyses and recommendations. These elements were reported to the local sponsor and to the Honolulu District and are also found elsewhere in the Committee's final report. Included here are a few of my own conclusions and observations that I wish to offer in addition:

a. Because of the extreme energy associated with this type of high velocity flood-control channel, the entire channel must be armored to ensure it will function properly during the design flood without failing.

b. Because of the desires of the locals, the Committee tried to find alternative means to provide this armored channel without merely paving it in concrete. These alternatives included:

(1) Partial paving with inclusion of large boulders anchored in the bed of the stream which could serve as a low-flow channel and also might allow the limited growth of native vegetation.

(2) Provision of grade control structures to control erosion with a series of paved or grouted-rock drop structures with derrick stone energy dissipaters and natural channel material between the drops.

(3) Deeply grouted revetments on each side of the channel to prevent under cutting of the channel bank (levee) toes.

For each alternative that reduces the amount of paving in the channel, the potential for instability increases. This translates into: more paving means less risk and less paving means more risk.

c. If drop structures are selected, based on our experience with drop structures in the Mobile District, the amount of drop should be in the range of only 3 to 5 ft. Larger drops than this have been very difficult to control without significant erosion to the adjacent channel and banks.

d. If paving is selected (recommended), I suggest that roller-compacted concrete (RCC) be used because RCC is not only more aesthetically pleasing, but it is also cheaper to install. I have enclosed some literature on the installation and use of RCC in overflow embankments and spillways. The quality of reproduction of this information is poor. Additional information on design and installation of RCC may be obtained from Mr. Kenneth D. Hansen, P.E., Senior Vice President, Schnabel Engineering Associates, Inc., 1888 Sherman Street, Suite 330, Denver, CO 80203, 303-863-0422.

Site Reconnaissance

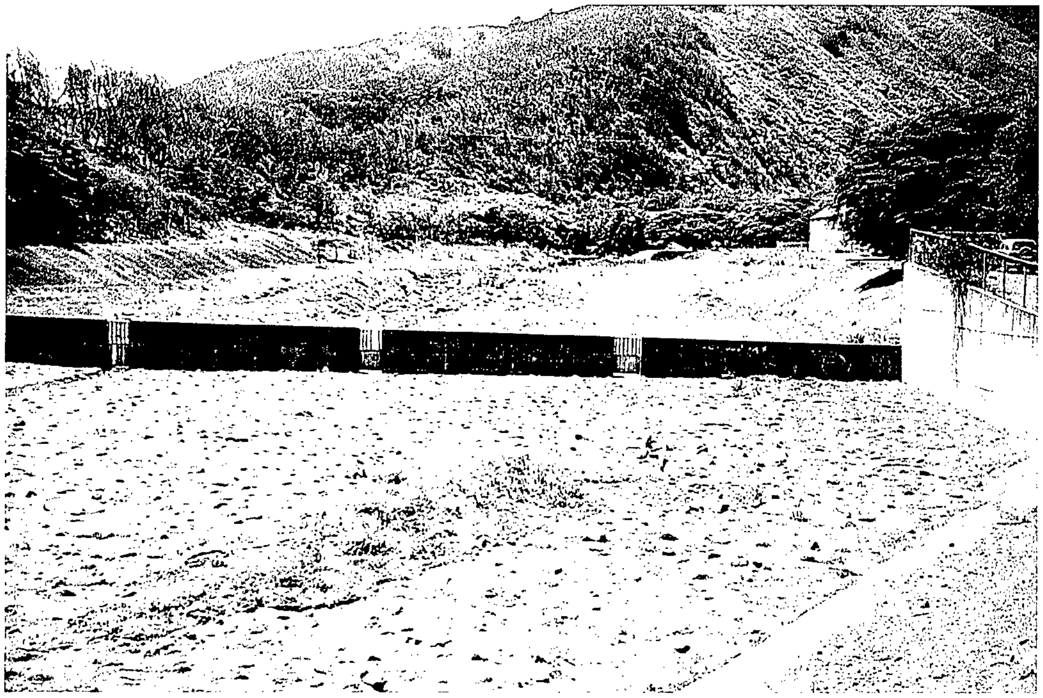

Photo 1. Sediment basin (Sta 127+00) upstream end of Iao Stream Project

Photo 2. Boulder-concrete channel downstream from sediment basin

Photo 3. Channel impingement at Sta 50+00

Photo 4. Local scour under grouted stone apron Sta 41+00 to 49+00

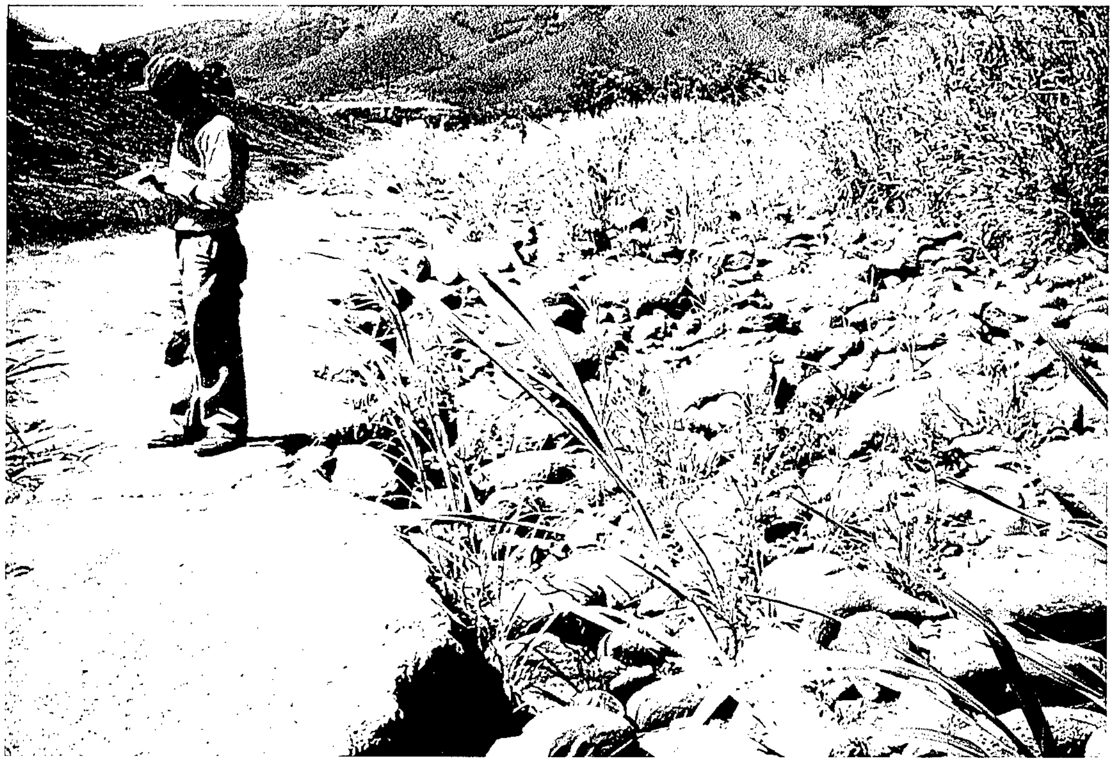

Photo 5. Toe apron Sta 41+00 to 49+00

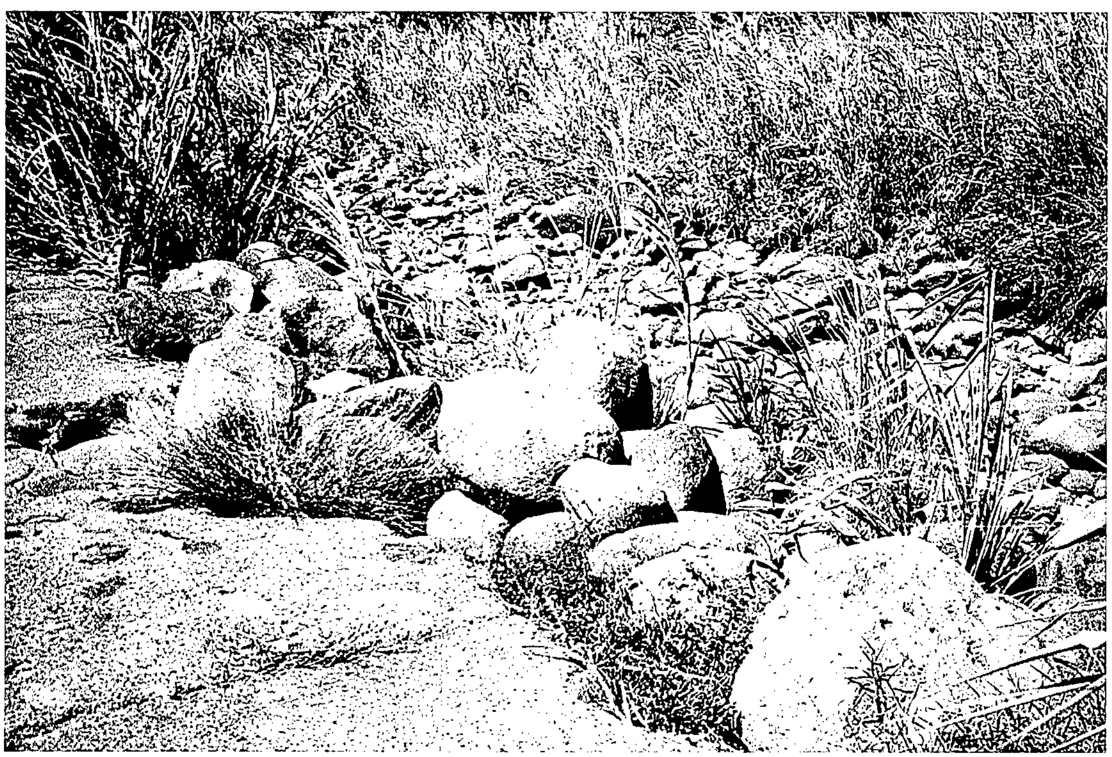

Photo 6. Repair to toe apron – Sta 41+00 to 49+00

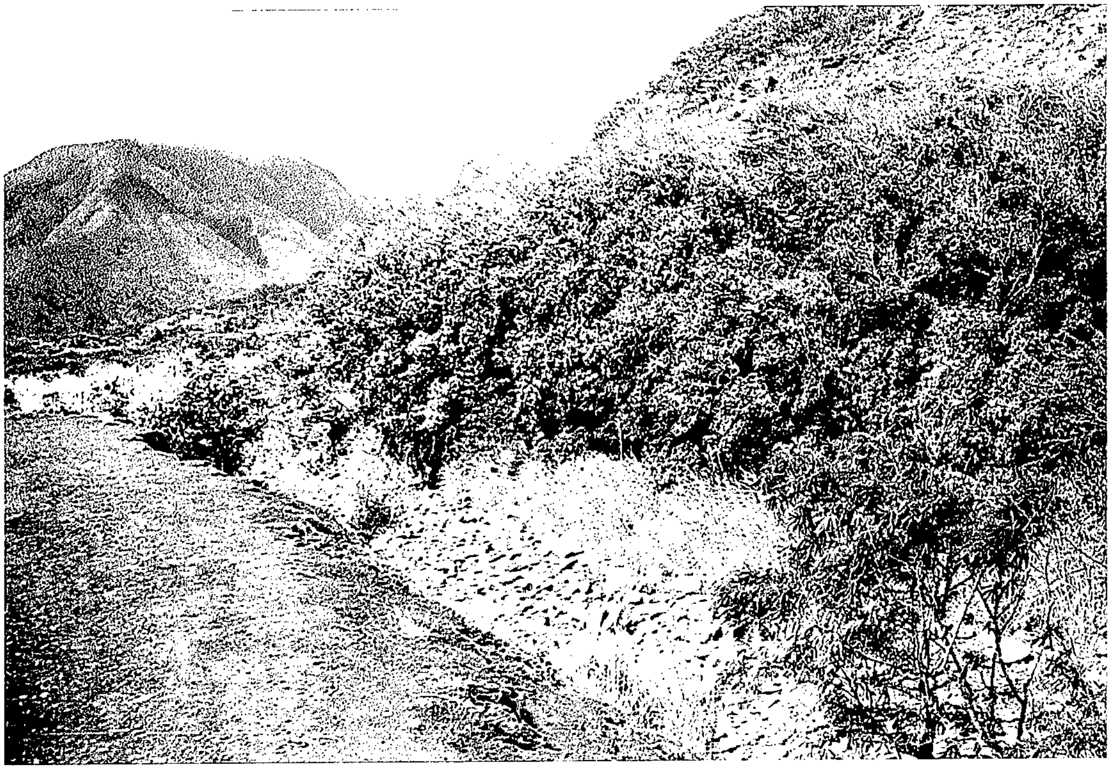

Photo 7. Constriction at Sta 40+00

Photo 8. Bank oversteepening due to toe erosion at Sta 40+00

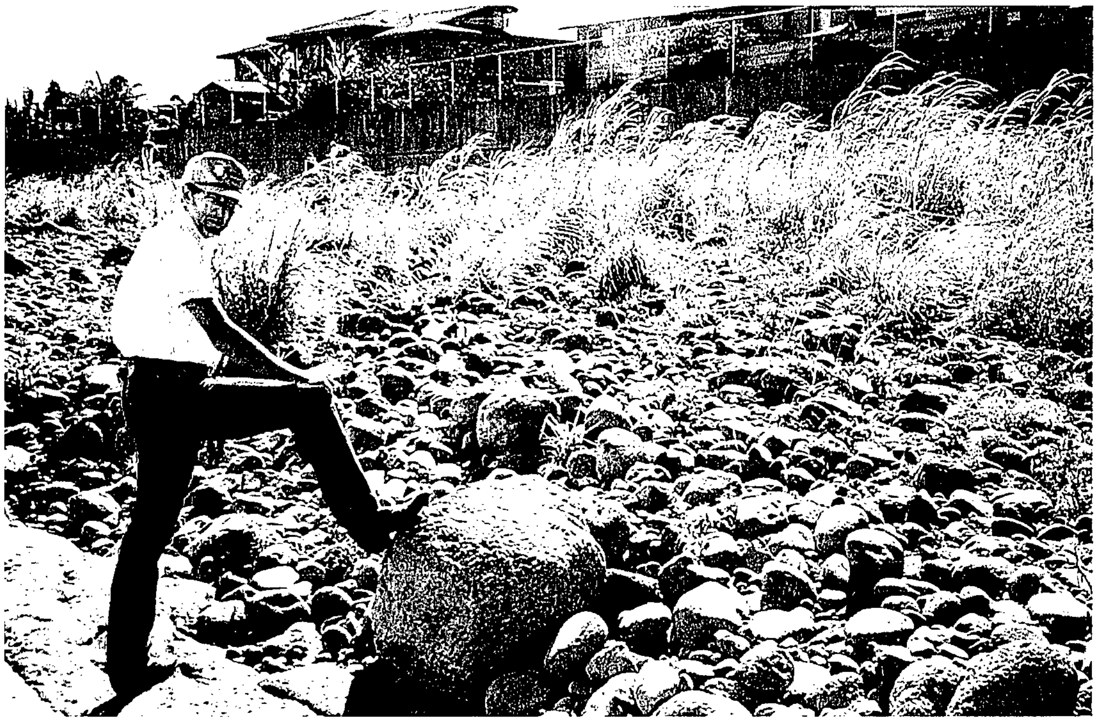

Photo 9. Deposition in boulder-concrete channel downstream from Waiehu Beach Road

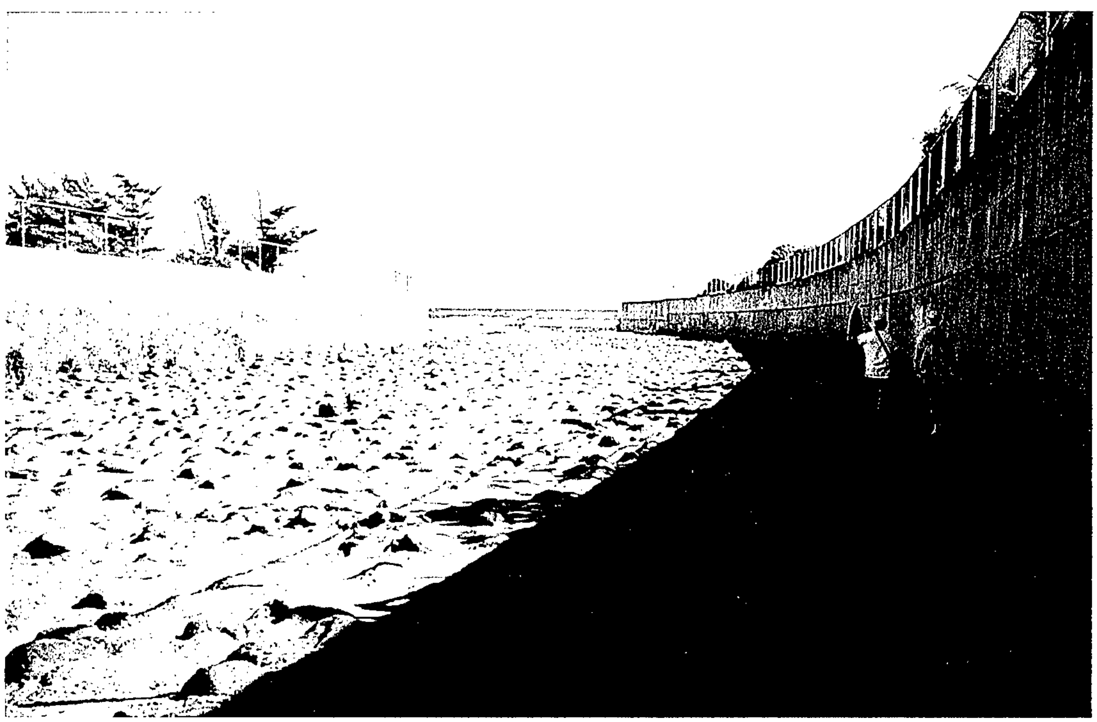

Photo 10. Downstream end of Iao Stream Project

Appendix A
Request for Assistance of the Committee on Channel Stabilization

DEPARTMENT OF THE ARMY
U. S. ARMY ENGINEER DISTRICT, HONOLULU
FT. SHAFTER, HAWAII 96858-5440

REPLY TO
ATTENTION OF
CEPOH-EC-T (1f)

9 August 1999

MEMORANDUM FOR COMMANDER, WATERWAYS EXPERIMENT STATION,
ATTN: CEWES-HR-M (RON R. COPELAND),
P.O. BOX 631, VICKSBURG, MISSISSIPPI 39180

SUBJECT: Request for Assistance of the Committee on Channel Stabilization

1. Request that the Corps of Engineers Committee on Channel Stabilization participate with the Honolulu Engineer District in a review of channel stability and levee undermining problems in Iao Stream, Maui, Hawaii. We propose the committee review the problems and provide cost effective structural and nonstructural recommendations. The Honolulu Engineer District will provide committee members with background information on the problems being experienced in Iao Stream. The project was discussed in a telephone conversation between Mr. James Pennaz (CEPOH-EC-T) and Mr. Ron Copeland (CEWES-CR) on 3 June 1999.

2. The review should be scheduled for the week of 13 September 1999. A tentative agenda is enclosed.

3. POC for this meeting is Mr. James Pennaz at (808) 438-5899 or Ms. Sharon Ishikawa at (808) 438-2249.

FOR THE COMMANDER:

Encl

JAMES L. BERSSON, P.E.
Chief, Engineering and
Construction Division

CF:
Commander, U.S. Army Engineer Division, Pacific Ocean, ATTN: CEPOD-ET-E/Mr. Wayne Hashiro, Bldg 230, Fort Shafter, Hawaii 96858-5440
Commander, U.S. Army Corps of Engineers, ATTN: CECW-EH/Dick DiBuono, 20 Massachusetts Avenue, NW., Washington DC 20314-1000

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
June 2000

2. REPORT TYPE
Final Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

Channel Stability Problems, Iao Stream, Maui, Hawaii

U.S. Army Engineer Committee on Channel Stabilization
Report of the 64th Meeting—September 1999

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Ronald R. Copeland and Dinah N. McComas, editors

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
AND ADDRESS(ES)

8. PERFORMING ORGANIZATION REPORT NUMBER

ERDC/CHL SR-00-2

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The U.S. Army Engineer Committee on Channel Stabilization participated with the U.S. Army Engineer Honolulu District in a review of channel stability and levee undermining problems in Iao Stream, Maui, Hawaii. The Committee provided cost effective structural and nonstructural recommendations. Iao Stream is part of a flood control project where maintenance costs must be minimized and aesthetics and wildlife habitat are important. Any project changes to ensure protection from the Standard Project Flood must be cost effective.

The Committee identified several significant natural processes that are currently adversely affecting Iao Stream. These included local scour due to flow impingement, generalized degradation, and headcutting. Geotechnical processes contributing to bank instability were also identified. Studies were recommended to better determine the relative significance of various processes. The Committee developed two conceptual designs for Iao Stream that met the project objectives of flood control and environmental enhancement.

15. SUBJECT TERMS

Bank stability	Flood control channel	Iao Stream
Channel stability	Grade control	

16. SECURITY CLASSIFICATION OF:

a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED		51	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18