Influence of Tree Roots and Mammal Burrowing Activity on Levee Performance

Prepared for:
California Levee Vegetation Research Program

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1.0 Introduction

The devastating flooding of New Orleans resulting from Hurricane Katrina brought to light the fragility of levee systems across the United States. The years following this disaster have brought a renewed focus on public safety and a closer look at policies, standards, and conditions of existing levee systems.

Consensus has not been reached with regard to the impact of woody vegetation on levee integrity. The presence of woody vegetation can introduce uncertainty in the reliability of levee performance. Trees and their roots have been suggested to possibly undermine the integrity of compacted earthen levees by providing enhanced and focused seepage through the levees. Further, windthrow of levee trees during large storms or hurricane events leading to concentrated flow through the levee or erosion and scour present additional concerns. Maintenance and access for inspectors is another stated reason for the USACE policy on vegetation. Alternately, live tree roots are believed to strengthen the levee and improve slope stability in many cases. The effects of roots of healthy woody vegetation on seepage patterns through levees are not well understood. Additionally, the removal of trees from levees may destabilize levees due to the decay of roots that remain after the trees are cut down.

These issues are explored through a collaborative effort initiated in California referred to as the California Levee Vegetation Research Program (CLVRP). Impacts of woody vegetation and animal burrows on levee seepage and slope stability are explored. The presence or absence of various types of vegetation correlated to animal burrowing activity and the relative impact of this activity was also considered as an integral part of this study.

The Seepage and Slope Stability aspects of the CLVRP are summarized in a series of 5 volumes, with an executive summary discussing key conclusions of each herein:

- **Volume 1:** Review of Literature and Case Histories
- **Volume 2:** Parallel Trench Wetting Front Test, North Levee of the American River at Cal Expo Sacramento, California
- **Volume 3:** Crown Trench Seepage Test, Northern Levee of Twitchell Island, Rio Vista, California
- **Volume 4:** Field Evaluation of Burrowing Animal Impacts and Effectiveness of Remedial Measures
- **Volume 5:** Modeling Tree Roots and Mammal Burrowing Effects on Seepage and Stability of Levees
2.0 Executive Summary

2.1 Volume 1: Review of Literature and Case Histories

Volume 1 provides a detailed literature summary based on our review of available case histories and data relating to the impacts of both vegetation and animal activity on levee performance. Based on the literature review, severity of this impact depends on tree and animal species, location of the tree, levee district maintenance practices, soil types and hydraulic loading the levee is subject to; thus, it is not appropriate to consider all trees as imposing the same level of risk to all levees. As observed from USACE incident reports, the majority of the reported vegetation related case histories point to vegetation as inhibiting maintenance and inspection, with none directly tied to an actual cause of levee failure. Conversely, several cases where vegetation was present along the waterside levee slope were reported to have limited erosion and fewer failures when compared to reaches without vegetation. In comparison, levee failures associated with animal burrowing appear to be well documented and apparently are a more common type of failure, given the larger, more continuous openings within an embankment produced by the burrowing activity.

2.2 Volume 2: Parallel Trench Wetting Front Test, North Levee of the American River at Cal Expo Sacramento, California

Volume 2 presents the results of a full-scale levee field test conducted to measure the effects of seepage in the vicinity of live and decaying tree root systems. The test was the first of a series of two such field tests and involved the construction of parallel trenches in the vicinity of a decomposing eucalyptus stump located along the landside of the northern levee bordering the American River adjacent to the California Exposition and State Fair (‘Cal Expo’). Levee embankment soils consisted primarily of silts, sandy silts, silty sands, and lean clays. Levee foundation soils consisted of interbedded lean clays and clayey silts underlain by sandy soils at relatively shallow depths. The tree was cut sometime between 1994 and 1998 and the stump left decomposing for 12 to 16 years prior to the field test. A live hackberry tree with healthy roots was present at the toe of the levee. A control set of parallel trenches was constructed away from the eucalyptus stump. During the test, the upslope trench was flooded and maintained at constant hydraulic head to induce slope-parallel seepage and the downslope trench was used to make observations and collect any intercepted seepage. Piezometers and tensiometers were installed to measure positive and negative pore water pressures within the zone of flow to describe the wetting and flow patterns as they evolved within the levee. Instrumentation was placed to specifically assess the influence of the stump and its decomposing root system. In addition to instrumentation data, visual observations were recorded during the 6-day flow test.
Decomposing roots, excavated following the flow test, displayed varying degrees of decomposition with voids or annular spaces in 39 percent of roots intersected by the excavation. Annular spaces were continuous over short distances, and many were partially or loosely filled with organic matter. Some roots had voids partially filled with organic matter and soil. Live roots growing from a hackberry tree located at the toe of the levee, mammal burrows, ant and worm holes, and a water pipeline added complexity to the system and the study. Small live roots were observed to be concentrated in the voids around and within decomposing roots. The field test benefited from the complexity of this site as these diverse conditions represent the reality of a levee system.

Tensiometer installation revealed the sealant materials (a silica slurry) could flow through a gap between the bark and woody core of a decomposing root at the lower trench wall face downhill from the stump. Silica slurry was found in several other roots as well as in loose soil pockets and cracks, but only where the tensiometer hole made a direct hydraulic connection with the void space.

We observed that where voids are shallow, seeps can form at the slope surface. Burrow networks, including gopher burrows (which are often partially backfilled as gophers excavate new tunnels) were found to be sufficiently continuous to flow once water enters the macropore/burrow. In this case, water entered the macropore through a direct hydraulic connection to the water source. In an effort to avoid influence of these burrows, burrow holes observed in the water delivery trench were shallowly plugged (to a depth of approximately 1 foot from the face of trench) prior to filling the trench with water. During the flow test, new holes previously not apparent were established with direct hydraulic connection to the water delivery trench and these influences dominated flow and wetting patterns. The presence of two gopher burrows greatly impacted flow patterns during the test and both were hydraulically connected to the water source. Though burrows dominated flow patterns and brought seepage to the slope surface, preferential flow through macropores diminished with time and with saturation of the surrounding soil matrix. Flow eventually stopped in the burrows. For a macropore to flow, the supply of water must be in excess of the lateral losses to the surrounding matrix and the macropore must be sufficiently connective to transport the water downslope. Absent a direct hydraulic connection, pore suction would prevent flow from smaller pores into larger macropores or voids. However, eventual saturation of smaller pores allows flow into larger pores as pore suction is eliminated and pore pressure is generated, driving flows into the discontinuity. As full saturation is achieved in the surrounding matrix, however, lateral losses are increased, and supply must keep pace for flow to continue. Further, continuity of void space is also necessary for flow.

Two ground squirrel burrows were encountered in the lower trench during excavation and neither was directly connected to the upper trench. These squirrel burrows encountered did not produce water until late in the test. Moisture appeared to concentrate into one of the burrows, but water never flowed. Without a connection to the water source at the upper trench, flow would be limited by the rate of water delivery from surrounding soils.
The roots were not sufficiently continuous to flow water from the upper trench to the lower trench through the levee soils. The presence of the stump impeded the rate of the wetting of the soil in the zone of decomposing roots.

2.3 Volume 3: Crown Trench Seepage Test, Northern Levee of Twitchell Island, Rio Vista, California

Volume 3 presents a summary of the results of a full-scale field infiltration experiment conducted along the crown of a bypassed levee. The test was positioned adjacent to an oxbow segment of the Sevenmile Slough, Twitchell Island, Rio Vista, California. An 8 ft deep crown trench was excavated into the center of the levee to intersect the root system of a land side live oak tree, a water side valley oak tree, and a control section. This field test was designed to evaluate the effects of seepage in the vicinity of live tree root systems. During the test, the crown trench was flooded and maintained at constant head to simulate a flood condition with water delivered from the center of the levee. Piezometers and tensiometers were installed to measure positive and negative pore water pressures, respectively, within the zone of flow to describe the wetting and flow patterns as they evolved within the levee and to specifically assess the influence of the live tree root systems.

Cracking was observed in the crown road along the levee crest within the first 24 hours of the flow test. After approximately 39 hours of flow, the waterside oak tree, initially leaning at an angle of approximately 44 degrees from horizontal, rotated approximately 20 degrees toward the adjacent slough, creating cracks and deformation along the waterside slope.

Observations and data collection were made before site construction, during trenching, throughout the 10-day flow test, after flow, and during restoration of the levee and backfill of the trenches. Data collected included:

- A 130 foot stretch of a delta levee logged in detail to a depth of 8 feet (10-foot levee height). Logs include detailed sketches of the root systems of nearby trees, burrows, and variable soil conditions.

- Pre-flow test inspection with Dr. Dirk Van Vuren of UC Davis to look at burrowing animal activity at the site.

- Soil borings and logging for each instrument location as well as 3 cone penetration tests along the levee crown.

- Continuous monitoring of positive and negative pore water pressures before, during, and after the flow test using a network of 48 instruments, including piezometers and tensiometers.
• Field observations of time and location of observed seeps along the surface of the levee.

• Field observations and monitoring of cracks and their progression throughout the test. This included observations associated with a fallen tree on the water side of the levee.

• Deformations associated with the studied trees and the crown road, analyzed through T-LiDAR analysis by Dr. Gerald Bawden and his team with the USGS.

• Manual monitoring of flow volumes through reading of a mechanical gauge connected to the pump system.

• Observations of seepage and preferential pathways during a 1-day tracer dye test.

• Post-flow site inspections to evaluate conditions that may have affected flow and to evaluate the age (60 years) of the fallen waterside tree.

• Aerial images were used to date vegetation and determine extent. The approximate age of the landside oak tree is estimated to be on the order of 25-30 years old.

• Blackberry groundcover present at the site corresponds well to where burrowing was most abundant at the site and aerial images helped to delineate the limits.

• The oxbow section of Sevenmile Slough flowed as part of the slough as of 1932. Around 1950, the Sevenmile Slough was gated. Topography in 1952 shows the flow channel of the oxbow section at the study site as a wetland. Two structures and an access road are present in the vicinity of the study area in 1932 and gone by 1952. Poor records exist for the period between 1920 and 1960 (URS, 2011). Exploration to define site stratigraphy and geotechnical conditions did not extend into the slough. Interpreted stratigraphic sections involved approximation of geologic conditions into the slough. It is unknown whether the natural levee clays and clayey silts disappear beneath the channel, but based on exploratory data, a low permeability layer is believed to exist, separating the flow of water in the slough from the groundwater at depth, and so the layer is shown beneath the sediment for the purpose of modeling.

Flows at the Twitchell Island test site were controlled by macroporosity and stratigraphic conditions related to the presence of an old levee on which the existing levee is founded. Zones of macropores associated with burrowing activities of muskrats (from the waterside), as well as voles and gophers (from the landside) advanced the wetting front when burrows intersected (or nearly intersected) the water source. As observed at the Cal Expo test site (discussed in the second volume of this series), flow of water through macropores which advanced the wetting front diminished with time. Concentrated seepage mitigation efforts during testing consisting of
Executive Summary

placing gravel bags over flowing seeps was sufficient to control flows until surrounding soils became saturated and concentrated flows reduced. Where burrows were far from the water source with open outlets, seepage was observed to increase at these outlets as the soils surrounding the burrows saturated. Flows through these burrows were limited by the permeability of the soils surrounding the burrow and as such, flows were slow and did not appear to trigger erosion. One burrow, mid-slope near the control line, appeared to have a direct connection to both the water source and the levee slope. A large pile of gravel bags and a straw wattle controlled flows and erosion of the slope until wetting of the burrow walls increased the permeability of the walls such that inflow did not exceed outflow and the burrow ceased to flow about 42 hours into the flow test.

Elevated pore water pressure was observed in one piezometer located at a depth of 3 feet directly behind the landside oak tree. The instrument within the same hole at a depth of 6 feet did not show elevated pore pressure relative to comparable instruments. A similar pattern was not found behind the waterside oak tree, though pressures behind the tree were observed to drop by 0.25 feet of head when the tree fell and pressures in an adjacent instrument increased by a similar amount. Observed seepage around the tree and surrounding muskrat burrows ceased once the tree had fallen and preferred water pathways appeared to shift to burrows to the north and south of the waterside oak tree. The leaning waterside tree was founded on soft, debris-laden, loose soils of the waterside slope and the thick and soft deposits of silts found within the adjacent oxbow section of the slough. There are many leaning and fallen trees along the waterside slopes of the Sevenmile slough. A tree like the waterside oak tree should be evaluated for health of the tree, size, and balance of the tree with consideration to species, soil strengths, benefits to erosion resistance of the levee, consequences of failure, consequences of removal given practical and cost constraints, and other relevant factors specific to each circumstance. The landside tree performed acceptably under saturated conditions and gusting wind conditions, showing a modest rotation of about 0.12 degrees (or about 2 inches measured 6.5 feet up from the base of the tree) based on LiDAR data provided by Gerald Bawden of the USGS.

Volume 4: Field Evaluation of Burrowing Animal Impacts and Effectiveness of Remedial Measures

Given that animal burrows had played a large role in each of the full scale testing efforts, Volume 4 explored the extent and architecture of burrow networks. Two different sites were selected to capture the effects of animal burrowing in levees with different composition as well as maintenance practices. The field studies were aimed to achieve two objectives:

1. Assess the extent and architecture of burrow networks under the two limiting conditions of: (1) no maintenance and regular (yearly) baiting; and (2) regular (yearly) grouting.
2. Study the efficacy of current DWR grouting techniques by injecting a cement-bentonite grout into the largest burrows, and a chemical grout to fill remaining void spaces missed by the cement grout.

Each test involved a two-phase grouting effort to allow for excavation of the burrow network and an evaluation of the efficacy of DWR grouting practices. Where DWR grouting efforts were not already in place, the first round of grouting was performed using the typical cement-bentonite grout mix employed by the DWR and local maintenance districts in their periodic grouting campaigns. This approach involved grouting holes typically targeted during regular grouting operations (8 cm in diameter and larger) using a portable grout rig and low-pressure system (0.5 psi). This step was not necessary if DWR periodic grouting programs were already in place.

Several days after the cement-bentonite grouting program was completed, a second round of grouting was performed, this time using a polyurethane-based grout (ten parts pink-dyed water and one part additive composed of Stratathane ST-504 injection resin from Strata-Tech Inc. and Sika® concrete bonding adhesive). The polyurethane was injected in a triangular grid pattern (approximately 1.2 m, or 4 feet, on center) with the intention of grouting void spaces missed by the DWR grouting program.

The first site was a section of a sandy levee with an active California ground squirrel (*Otospermophilus beecheyi*) infestation, and with minimal maintenance and mitigation practices in place. The study site was a levee bordering the eastern margin of the Sacramento River, several miles upstream of Sacramento, California. No periodic grouting or baiting practices were in place at this site at the time of study and therefore grouting was completed in a two-phased approach.

During inspection of the area several large active California ground squirrel burrows were encountered along a stretch of the levee adjacent to a cornfield, and a 20 meter (60 feet) long segment encompassing some of the largest burrows within this reach was selected for the test. Seventy-two burrows were surveyed on the landside slope; thirty-four burrows were encountered on the waterside slope, and six along the crown of the levee. The abundance of burrows on the landside relative to the waterside of the levee was attributed to landside proximity to a corn field, a food source, and soil conditions with more layering and a clayey zone, enhancing burrow stability relative to the sandier waterside slope.

The second site was a smaller levee with a clayey embankment along the west levee of Cache Creek north of Woodland, California. Similar to the sandy levee, this site also had an active small mammal food source very near the landside toe of the levee. The creek channel is located 20 meters away from the levee and has incised into its bed therefore the levee is infrequently wetted during the flood season. This site is of great importance to the history of grouting practices in California. During the floods of March 1998, this levee experienced water levels within 0.5 meters of the crown. Sustained high water resulted in several sand boils and through-seepage on the clayey embankment. This near failure was attributed to the presence
of mammal burrows, which led to the beginning of current DWR grouting and maintenance programs.

In general burrowing activity at the Clayey Levee site observed during this study was mainly by Pocket gophers, with a few isolated California ground squirrel burrows. Typical burrows had diameters ranging from five to ten centimeters, and were mostly concentrated in the upper half of both landside and waterside slopes, coinciding with a strip of grass that was not mowed by the land owner.

Given this site was last grouted by DWR during late summer of 2011 (10 months before this study) it was deemed unnecessary to re-inject cement-bentonite grout before injection of the polyurethane based grout. One burrow at the Clayey Levee site extended all the way through the levee. The burrow was encountered approximately 1 to 1.2 m (3.3 to 4 ft) below the levee crown and connected to a series of short burrows. The burrow extending through the levee was completely grouted with cement-bentonite grout from the DWR grouting program.

Burrow networks at both sites were found to be more extensive on the landside levee slope than the waterside slope, coinciding with the slope nearest to the food source (cornfield for the sandy levee and orchard for the clayey levee). Layering and soil type was also observed to have a strong influence on the amount and extent of burrowing on the sandy levee. At the Sandy Levee, burrows followed an interface between a stiff fine-grained or cemented sand layer overlying the loose sand material composing most of the embankment, most likely because the animals prefer to dig through the loose materials, while at the same time having a stiff and stable roof. Several other burrows were encountered exclusively along the stiff fine-grained layers in the levee embankment. Similar patterns of burrowing activity following interfaces of clayey and sandy soils were observed at Cal Expo and Twitchell Island test sites (discussed in Volumes 2 and 3).

Between the two sites, DWR grouting methods were successful in filling between 70 and 80% of the existing burrows at the two test sites. While the two sites were widely different in terms of levee material and maintenance practices, there are similarities that point to the effectiveness of the cement-bentonite grout treatment, as well as some of its shortcomings.

Most of the large, open burrows were effectively grouted with cement-bentonite and most of these burrows appear to be connected, forming large complex burrow systems. Complete filling of these systems is a difficult task due to the viscosity of the fluid. Several instances of partially filled holes with voids within the hardened grout were observed in both sites. Also, maintenance crews limit grouting efforts to large (10 cm diameter or larger) open burrows, leaving potentially large holes ungrouted, if their entrances were collapsed prior to grouting. Through the implementation of a regular, ongoing grouting program the amount of cement bentonite grout needed to fill burrows decreases over time, which would correspond to reduced maintenance effort and reductions in yearly materials and manpower costs over time. Moreover, the site with no regular grouting program was observed to have significantly larger
open burrow networks, which could lead to seepage and stability problems such as those described in Volume 1.

An important unknown is the long-term performance and effect of grouting on seepage and stability of a levee. After decades of injecting grout into levees, the conditions of the embankments will surely change as the levee material is replaced by grout.

Overall, current cement-bentonite injection practices prove a useful tool in grouting most of the large active burrows on a levee, as long as regular maintenance is performed. However, there is always a possibility that large holes are missed and these holes may completely penetrate a levee embankment. Thus, grouting activities have to be supplemented by regular patrolling and generation of activity databases for maximum benefit.

2.5 Volume 5: Modeling Tree Roots and Mammal Burrowing Effects on Seepage and Stability of Levees

The influence of woody vegetation on seepage through levees was evaluated by performing a series of transient seepage analyses using data obtained from the field seepage tests described in Volumes 2 and 3. Results of these seepage analyses were used to evaluate stability of the levees at each of the full scale seepage test sites. A separate series of analyses was carried out to assess the influence of mammal burrows on seepage through levees using the data obtained from the field mapping of ground squirrel burrows also performed as a part of this effort, as described in Volume 4.

The data gathered during the seepage field test program demonstrate that wetting fronts tend to progress more slowly through and around a root system than through levee sections with no roots, suggesting that the discontinuities found around some roots have little influence on accelerating groundwater flow and low likelihood of initiating internal erosion processes. These observations are supported by the results of an extensive set of seepage numerical simulations, which show discontinuous voids, such as could be formed by decomposed root systems, do not provide a direct seepage path in which high flow velocities could develop. In cases where a given root is completely decomposed, its space is generally filled with decomposed biomass, and tends to be looser than the surrounding soil, creating zones of higher hydraulic conductivity. However, while this condition could produce a faster advance of the wetting front, by relatively rapid saturation of localized zones within a levee, the flow quantities and velocities would not be high enough to trigger piping or internal erosion processes.

Mammal burrows clearly have a much larger influence on internal erosion processes than tree roots given their larger diameter, length and continuity throughout a levee embankment than the live and decomposed roots observed in this research program. Of special interest are burrows or burrow networks that extend from a waterside slope towards a landside slope, such as the one encountered on the clayey levee (Volume 4). These conditions have the potential of eroding levee material because the flow velocities can potentially reach critical values to trigger
piping. These observations are supported by numerical simulations performed to back-calculate the field seepage (flow) tests, and a historical account at one of the mammal burrow sites.

Overall, a number of factors govern seepage patterns in a levee including the continuity of the macropores, their location and distribution vertically and horizontally, and the type of soil which governs the rate of saturation. Also, deeper mammal holes or macropores connected to the waterside of a levee will be subject to larger hydraulic heads, and thus higher flow velocities than those located near the levee crest. However, piping can also be triggered along relatively shallow discontinuities, as long as they are directly connected to a hydraulic load and have an exit face. On the clayey levee on Cache Creek, piping occurred along a burrow which experienced a head of about 80 cm (2.5 ft).

The degree of saturation and the amount of water flowing into a macropore not directly connected to the water source is dependent on the hydraulic conductivity of the soil. Unsaturated fine-grained soil will have very low conductivity and thus the flow of water into the macropore will consequently be low. As saturation increases, discharge into the macropore will increase. Conversely, for a macropore open to the water source (i.e. – hydraulically connected), saturation levels of the surrounding soil (the walls of the burrow) control the rate of exit seepage and can reduce overall flow through the macropore as water instead travels more freely back into soils surrounding the macropore (i.e. – burrow). Finally, the continuity of levee macropores is critically important. Continuous water side macropores or macropores terminating a short distance from a land side macropore can produce very high hydraulic gradients and potential for piping.

The slope stability analyses presented in Volume 5, using data from the flow tests performed and from subsequent seepage simulations, demonstrate that the presence of a tree has little to no effect on factor of safety against seepage-induced instability. Factors of safety were nearly identical or slightly higher for the levee sections with a tree as opposed to those without a tree. The effects of tree lean and wind can place a load on a slope; however, that is likely to vary with a variety of local conditions and tree species. Such loads can be evaluated using a simplified approach consisting of mass-averaged 2D modeled sections. Tree loading is applied over a zone determined by the size of the root plate, estimated with the best windthrow data available for the tree (based on tree species, size, etc.). Advances in our understanding of root architecture and windthrow dynamics and their application to these types of analyses, as well as advances in slope stability software that incorporates tree and root reinforcement and tree loading, would allow more precise modeling of trees in future levee slope stability analyses. In summary, our observations, data and analyses suggest:

- The presence of a tree has little to no effect on factor of safety against instability. Factors of safety were nearly identical or higher for levee sections modeled with a tree compared to those without a tree.

- The Twitchell Island waterside valley oak tree appears to have fallen due to horizontal forces placed on the root system associated with extensive tree asymmetrical growth,
3.01.0 Seepage and Slope Stability Conclusions

tree lean, and wind loading. The most likely failure simulation for the waterside oak tree is study simulation B-2, where the failure that was simulated extends to the hinge-point of the waterside slope. Our data suggest the flow test did not influence the slope movement or rotation.

- The Twitchell Island landside valley oak tree did not fail under similar saturated conditions and gusting wind conditions, showing rotation of about 0.12 degrees (or about 2 inches measured 6.5 feet up from the base of the tree) based on LiDAR data provided by USGS.

3.0 Seepage and Slope Stability Conclusions

The study involved a comprehensive literature review, two full scale field seepage tests, two burrowing mammal investigation excavations, and supporting seepage and slope stability modeling associated with field seepage tests and burrow investigations. In general, the literature review was consistent with the results of field testing.

USACE incident reports show levee failures associated with animal burrowing appear to be well documented and apparently are a more common type of failure, given the larger, more continuous openings within an embankment produced by the burrowing activity. The two field seepage tests, two burrow investigations, and associated seepage modeling efforts performed as part of this program find results consistent with USACE incident reports. Results show that in terms of seepage velocities, time of saturation, and piping potential through a levee, the presence of animal burrowing has a much larger influence than roots, given their larger diameter, length and continuity throughout the embankment.
4.0 Recommendations for Future Work

The impacts of woody vegetation on overall levee integrity may be better understood through further research. Throughout this program of study, the authors have had the good fortune to hear the opinions of numerous researchers, experts, state and federal agencies, private consultants, and local maintaining authorities on the impacts of woody vegetation on levee performance based on varied experiences. For this highly interdisciplinary subject to be well understood, the problem must be placed within a risk framework where all factors impacting levee integrity and performance can be considered and vegetation effects evaluated in terms of their relative risk. Further, given the interdisciplinary nature of the work, this research does not address all key factors needed to understand the impact of woody vegetation on levee performance. Further study to evaluate the positive and negative impacts of woody vegetation with respect to erosion would be useful, as this is an important element in understanding piping and through-seepage issues.