AMENDING THE CURRENT LEVEE BREACH RESPONSE PROTOCOL IN THE CALIFORNIA DELTA

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Abstract: California's Sacramento – San Joaquin Delta has fragile levees subject to several trends such as sea level rise, subsidence, changing inflows and earthquakes that make them increasingly prone to failure. Multiple levee failures "has the potential to draw in large volumes of salt water from the San Francisco Bay, turning the Delta into a brackish estuary" (EDAW 2007). This is a major problem that should be avoided or minimized since emergency response simulations indicate that "drinking water [is] a critical and key resource in both the response to and recovery from a disaster" (Bowen 2010).

A levee failure cannot be absolutely avoided but its consequences can be minimized. In this report, the current levee breach response regimen will be examined in order to pinpoint its weaknesses. The current system is the Delta Emergency Rock and Transfer Facilities Project which is run by the CA Department of Water Resources and has been implemented in past situations. This report will then look at recent developments in flood fighting technology and will assess whether adding these new elements to the current system would be beneficial. These new technologies would not be able to completely replace the current emergency response regimen, but they may have the capacity to improve the system as a whole. In conclusion, it was found that these new technologies have the potential to greatly improve the entire system's response time, but without field tests, it is unclear whether their performance will stand up to the conditions in the Delta region.

INTRODUCTION

The consequences of a major flood in California's Sacramento – San Joaquin Delta (referred to in this paper as simply the Delta) would be catastrophic. Short term consequences could include loss of life and property for the residents of the region, a major interruption in fresh water supply to roughly two-thirds of the state's population, and the loss of a large portion of California's farming economy. These short term consequences have the potential to become long term if a reliable water supply cannot be restored and if fields lie fallow for long periods of time due to salt water intrusion.

Policy makers are not blind to the risk of failed levees. In February 2006, Governor Schwarzenegger declared a state of emergency for the state's levee system which allowed him to allocate funds toward solving the problem. Many of these funds went into projects run by the California Department of Water Resources (CA DWR or DWR). The fact that this state of emergency was declared just months after the Hurricane Katrina disaster in New Orleans was no coincidence. There are many similarities between the Sacramento and New Orleans levee systems and an earthquake in California could be just as devastating as the hurricane was in Louisiana.

Since the levees are California's first and only line of defense against a flooding disaster, responding to and stopping a breach is of the utmost importance. That is why the system chosen for study in this paper is the current emergency response regimen to be activated in the event of a levee breach. A general picture of the current system can be seen in the flow diagram in Figure 1. Specific information can be found in the "Background" section.

In addition to an examination of the current system, new flood fighting technologies and innovations will be considered. Some of these technologies have been successfully implemented in other flood-prone areas. The main question posed here is whether these new technologies will be able to perform in the harsh conditions present in the Delta. If these new technologies do seem resilient enough to perform in the Delta, the recommendation will be made to incorporate them as a sub-system into the emergency response protocol, thereby improving overall quality and reliability.

BACKGROUND

California's Sacramento – San Joaquin Delta was "developed during the late 19th and early 20th centuries to reclaim more than 450,000 acres of freshwater and brackish marsh for agriculture" (Suddeth, Mount and Lund, 2010). Currently the levees in the federal system protect 1.5 million acres, more than 200,000 parcels of land, more than 600,000 people and more than $50 billion in property, all of which is in the Delta region (Mayer, 2010). The Delta system provides "conveyance to local and statewide water supplies" (EDAW, 2007). The Delta includes 60 islands protected by 1,100 miles of levees much of which is not part of the federal or state systems but is maintained by local agencies (EDAW, 2007). There are critical pieces of infrastructure located in the "Legal Delta" such as the Delta Mendota Canal, the California aqueduct (and their pumping plants) and several smaller aqueducts that deliver water from Northern California to Central and Southern California.

A good example of this critical infrastructure is the Mokelumne Aqueduct which is the main sources of water for the East Bay Municipal Utility District (EBMUD) (Prashar et al, 2009). EBMUD serves approximately 1.3 million people in the Oakland Bay Area and they provide support to neighboring

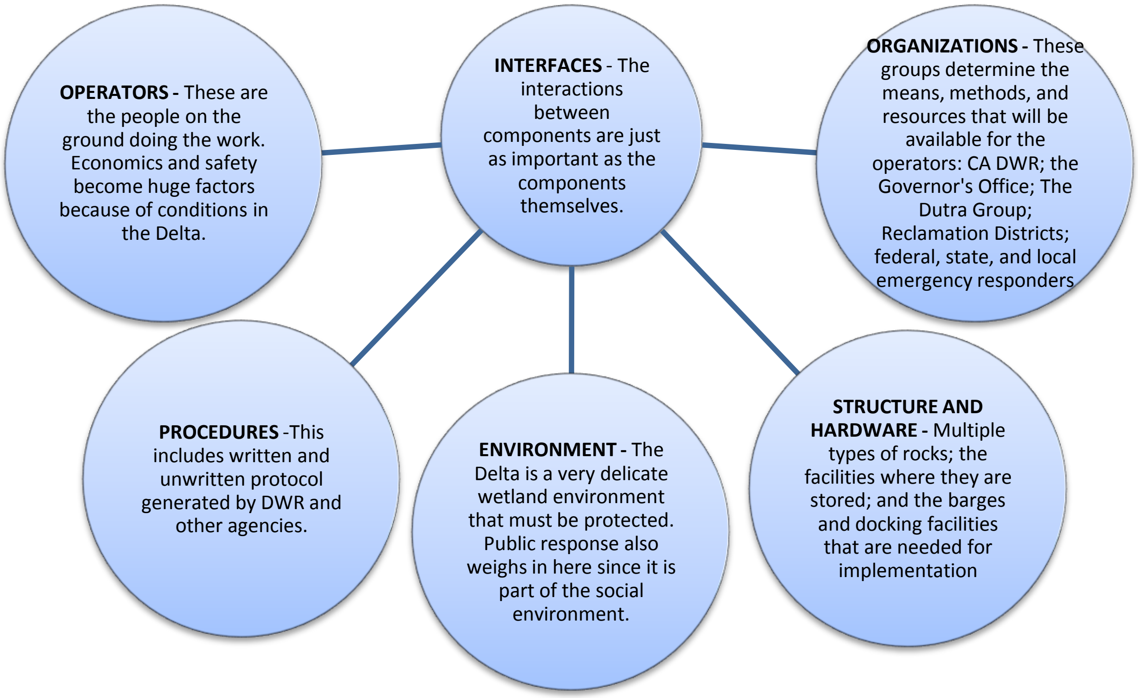

Fig. 1. Components of the current emergency response system for a Delta levee breach

districts (like the Contra Costa Water District) if help is needed. The Mokelumne Aqueduct consists of three large diameter steel pipes which run through the Delta region (including 5 islands) for approximately 15 miles. If a flooding disaster in the Delta were to disrupt the Mokelumne Aqueduct, one of the Bay Area's largest sources of fresh water would be unusable.

The Delta Levee system is "rigid and brittle" with "poorly constructed, weak seismically unstable foundations" (Suddeth, Mount and Lund, 2010). Originally constructed as small private structures, most levees do not meet current engineering standards, yet their load has expanded over time to include persistent problems such as land subsidence, sea level rise and erosion (Suddeth, Mount and Lund, 2010). With this in mind, levees will most likely fail due to "slumping, rupturing, erosion or overtopping during storm events" but can also fail due to "internal degradation that has occurred over time with seepage or from slumping and cracking that allows water to flow through and over the levee" (Suddeth, Mount and Lund, 2010). All of these possible failures are made more likely by poor foundations and weak construction materials that cannot cope with land subsidence, sea level rise and erosion.

Even with these probable failures, the main problem, as is generally the case with aging infrastructure, is money. Several key decisions that have not been made have hindered the ability of state and local authorities from taking action. For example, California policy makers must decide if they want to distribute state and federal funds by either equally mitigating flood risk throughout the levee system or concentrating in specific locations to reduce possible impacts to state objectives (i.e.: water supply, ecosystem restoration, transportation, recreation, and the economy). California policy makers would never officially rank islands or regions by priority to determine which islands merit more assistance. However, there is a priority list generated in Section 10 of the Delta Risk Management Strategy (DRMS), published by URS Corporation which aids policy makers in deciding how funds will be distributed (URS, 2008).

The political unknowns coupled with the high probability of failure means that engineers must work with a system already in place to at least lessen the impacts of a breach or failure. A historical perspective of the interface between engineers and policy makers was clearly seen during the Jones Tract levee breach in 2004. Categorized as a sunny day failure, this event caused a cascade effect and highlighted the significance of the Delta to California's well-being. While the exact time the breach began is still unknown, there were major effects on the water supply system. It "pulled 150,000 to 200,000 acre feet of water on an area of 12,000 acre" which also means that "as water river was pulled in, increased sea water intrusion became a concern" (Division of Environmental Services: California Department of Water Resources, 2009). Sunny day failures pose the most significant threat to the clean water system since there is a decreased amount of fresh water coming down the Sacramento River to combat salt water intrusion. During the

Jones Tract disaster, the fresh water releases from Shasta and Oroville reservoirs were increased to mitigate this issue.

In all, the total damage was "nearly $100 million for emergency response, damage to private property, lost crops, levee repair and pumping water from the island" (Flood Warnings, 2005). California policy makers already knew how delicate the Delta levee system was (the first dramatic island flood was in 1972), but the Jones Tract levee breach served as a stark reminder. Following the breach, the rock stockpile project was implemented. The purpose of the rock stockpile project is to "prevent loss of life, minimize property damage, reduce significant environmental impacts and protect Delta water quality and supplies when floods occur in the Delta" (EDAW, 2007).

The Current System

The Delta system is comprised of project and non-project levees. Project levees make up roughly one-third of the total and are controlled by DWR (Suddeth, Mount and Lund, 2010). The non-project levees were built by private or local interests and are largely maintained by local reclamation districts with state oversight. In this research, the emergency response capabilities of both DWR and one local agency, the Ironhouse Sanitary District, are examined in the event of a levee breach. Both entities have rock stockpiles and equipment ready to go should a disaster occur.

The primary uses for the rocks at flood sites in the Delta are three fold: "[1] to fight flood before a levee breach which may involve placement of rock to armor against erosion, mitigate crest settlement, add freeboard and address other slope stability issues… [2] *to armor ends of breach and close the breach and rebuild the failed section of the levee and armor critical portions of the levee interior* [Italics added]… [and 3] to construct temporary channel closures at strategic locations to protect areas from saltwater intrusion and reestablish municipal and agricultural water supply operations in the Delta" (EDAW, 2007). This research focuses on the second item, especially in terms of closing a breach as quickly and efficiently as possible.

DWR currently has two rock stockpiles in place at the Port of Stockton and Rio Vista. There is a loading facility at a third site in Hood, but as of yet, no rocks or supplies have been deployed there. These three stockpiles are for the sole purpose of providing emergency response materials should a levee be compromised. All three sites are referenced on the map in Figure 2 and the satellite photos in Appendix A. There are other stockpiles, such as those belonging to the CA Department of Fish and Game, which are used for other projects such as the Temporary Barriers Project. Although these projects are similar in operations, they have a much different purpose and will not be addressed in this report.

The Port of Stockton stockpile is located on Rough and Ready Island and stores 130,000 tons of rock. No site improvements were necessary when the Department of Water Resources leased both the outdoor storage and two acres of gravel covered open storage area from the Port of Stockton. Barge loading equipment was made and assembled by The Dutra Group. Once assembled and tested, the equipment was taken apart and stored on site. When needed, it can be reassembled by a land-based crane in a minimum of three days. Once in production, the Port of Stockton facility loads 500 tons of rock per hour onto barges.

The Rio Vista stockpile sits on 3.6 acres which are owned by The Reclamation Board. This stockpile holds up to 100,000 tons of rock. The Dutra Group has their own facility about one quarter of a mile away, so in the event of an emergency, rocks will be trucked to The Dutra Group facility where the infrastructure is in place to load them onto the barges.

If the initial plan is carried out, the Hood stockpile will be the smallest of the three, holding up to 10,000 tons of rock. As with the other sites, it will require a truck or barge for rock transportation. The site is located along the Sacramento River and River Road. The surrounding area is mostly owned by private warehouses, and a subsidiary of The Dutra Group is leasing the stockpile site to DWR (EDAW, 2007).

During a flood disaster, DWR is the lead agency on any project levees. They are also obligated to give aid to non-project levees, such as the ones on Jersey Island, mentioned later in this section. The procedure for fixing non-project levees starts and ends with the local district. First, the compromised levee is identified and DWR is informed of the problem. DWR then sends out geotechnical engineers to examine the situation and to work with the local district to formulate a repair plan. Throughout the repair process, DWR's technical and engineering resources are made available to the local district. If the situation worsens, DWR will send out an instant command team and will take over management of the operation. Otherwise, control stays in the hands of the local district. The cost for repairing a non-project levee is paid for by the local district. If local money runs dry, DWR supplies funds up to a certain amount. Once that amount is reached, an application is made for federal money. Once the situation is mitigated, DWR will pull its resources and the local district will be the sole entity in charge of the levee once more.

The Dutra Group, mentioned several times in this section, is a very important part of the emergency response process as they are the foremost barging entity in the Delta area. They are well-equipped in terms of equipment, trained personnel, and experience to handle a flood emergency in the Delta. If DWR's rock stockpiles run out, The Dutra Group can provide material support since they own and operate their own quarry in San Rafael, CA. The Dutra Group also takes a risk adverse approach in the Delta by having spare barges already loaded with rock during winter months when their work load is less. This means they can deploy material immediately after receiving a phone call from DWR. The Dutra Group understands how disruptive a Delta disaster will be to California's economy and general health, so they take steps to make sure their part of the disaster relief is as efficient as possible.

Jersey Island, located in the western most part of the Delta and number two on the DRMS priority list, is owned and maintained by the Ironhouse Sanitary District (also known as Reclamation District 830). As general manager Tom Williams can attest, Ironhouse is no ordinary sanitary district. With fifteen miles of aging levees to maintain, and the conviction

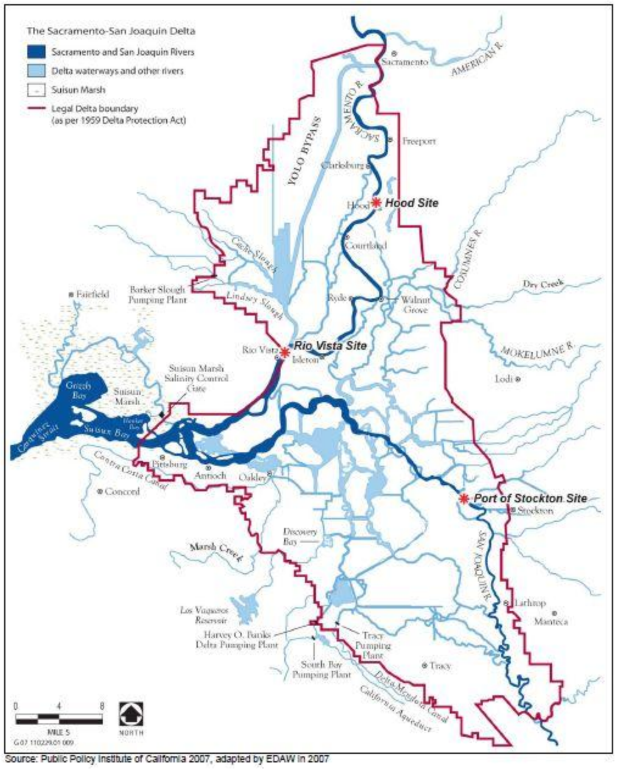

Fig. 2. (Left) Map of the three DWR rock stockpile facilities
Fig. 3. (Right) Interface between improved and non-improved levees on Jersey Island

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that California's fresh water supply will be compromised if the island fails, Williams and his crew have their hands full. They have two rock stockpiles and numerous pieces of equipment located on the island. There is a staff of twelve on the island every day and levee patrols are constant. Since coming on board in 2000, Williams has overseen the strengthening of many of the levees on the island. The work happens in a piecemeal fashion, since funding is hard to come by, but Williams is always looking for new revenue sources. The difference between an improved and unimproved levee can be seen in Figure 3.

Aside from maintaining and strengthening levees, Ironhouse also treats wastewater from their constituents, runs approximately 2,200 head of cattle, and grows hay. The cattle help to control weeds and they garner a profit of $250,000-$400,000 every year which can be put back into the island. Growing hay is part of the water treatment process. After going through the treatment plant, the water is used to irrigate the hay and any remaining chemicals are soaked up and eventually removed when the hay is cut. The clean water is then absorbed back into the ecosystem. Ironhouse is currently in the process of building a state of the art waste water treatment plant, so that water can be discharged directly into the San Joaquin River.

When asked how the Ironhouse Sanitary District will respond to a disaster involving one of their levees, Williams referred to a storm that took place in the winter of 2005-2006. During the storm, the winds shifted and began blowing directly from the west which buffeted the levees with wind and waves. Patrols around the island identified a levee that was in danger of breaching and immediately sent up an alarm to DWR. Unfortunately, they were already over stretched and did not come through with any personnel or supplies. Fortunately, Ironhouse was prepared for just such an event. They had 500 tons of rock stockpiled on the island and they used all of it to repair the levee before it broke. This storm made a few things clear to Ironhouse: being number two on the DRMS priority list did not increase the reliability of DWR and they needed a bigger rock stockpile (it has since been doubled in size).

New Technology

While researching recent innovations in flood fighting, the first system to note is a tough fabric, incompressible tube (Figure 4), recently developed by Donald Resio, senior technologist in the Coastal and Hydraulics Laboratory at the U.S. Army Corps of Engineers Engineering Research and Development Center in Vicksburg, Mississippi (Sawyer, 2009). Resio said, "With visions of choppers bombing breached levees in New Orleans with sandbags for days, the

Fig. 4. (Left) The tube in a small scale test in Stillwater, Oklahoma
Fig. 5. (Right) AquaDam® cutting off a levee breach in Humboldt Bay, CA. The AquaDam® is 8 feet high and 450 feet long.

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challenge was to find a better way." With this motivation and with funding from the U.S. Department of Homeland Security, Resio and his team found a simple response to a complex need. "A tube of non-stretch fabric, longer than the breach and of a diameter larger than the water depth at the gap, is dropped into the flood and 80% filled with water." Implementation involves dropping the tube off of a barge and letting it fill with the required amount of water. Then, using the forward motion of the water and lead lines, the tube is floated into place until it wedges itself tightly into the breach.

In depth information on this tube proved elusive, but even without it, a few key weaknesses are evident. The biggest problem is implementation. The tube must be dropped off a barge and floated into place. This implies that the barge will be able to hold itself stationary, quite a feat considering that water would be rushing around it to flow through the breach. It also implies the need for a system of ropes and pulleys able to guide the tube, through choppy and quick moving water, until it fits snugly into the breach. Although this method worked during scaled testing in Stillwater, Oklahoma, the conditions there were calm and controlled, very different from the turbulent conditions in the Delta. Furthermore, if emergency response crews can manage to float the tube into the correct position, it relies on the adjacent levees to keep it in place. If the section of levee in question is weak enough to breach, it is doubtful that the sections adjacent to it will be strong enough to support the tube. For these reasons, it is realistic to conclude that the tube will not benefit the current emergency response system and does not require further analysis.

Another technology is the AquaDam® (Figure 5). This technology was first invented by David Doolaege in the late 1980's. During that time, the main method used to control floodwater was to build a structure with sandbags or to push up mud levees. Doolaege realized the limitations of the sandbag method, mainly that it is often far too slow and labor intensive. He also recognized that the weight of all the sandbags made the structure stable and difficult to move. As a result, Doolaege came up with the idea of taking advantage of a different material – water. Compared to sand, the weight of water is about half, but its workability is much greater and its cost is much less. Thus, accessibility and economy are two benefits associated with using such water-filled structures.

Although AquaDam®'s construction is similar to the tube in theory, it seems to overcome the problems with ergonomics and strength inherent in the tube model. It consists of two polyethylene liners contained by a single woven geo-tech outer tube with the capability to add on more outer woven layers to increase its strength and durability. The basic premise is that the two water-filled tubes will create a "stable, non-rolling wall of water" (Doolaege, 2010). AquaDam® is installed by rolling out the tubes, one foot at a time, and using water pumps to fill them. After a successful installation, it can be used to contain, divert, and control the flow of the water. According to Doolaege, most of the AquaDam® structures can be set up and placed within a short period of time. In the case of a levee breach, timely implementation of a protection system may prove to save money and lives.

In a levee breach scenario, there are many ways to employ an AquaDam®. Three possibilities will be explored here. The first is to simply stretch the dam from one end of the breach to the other to fill in the gap. This application has many of the same problems as the tube developed by Resio since there is still no infrastructure holding the dam in place, and it would be very hard to install in Delta conditions. Also, the ends of a levee breach are jagged, which would compromise the seal between the AquaDam® and the soil. The second option is to create a half-moon shaped dam around the breach on the water side of the levee.. Yet again, implementation would be extremely difficult in Delta conditions, especially since it would most likely be necessary to employ more than one AquaDam® (attached with collars). The third option is to create a half-moon around the breach on the land side of the levee (similar to the configuration shown in Figure 5). This application shows promise for a number of reasons: vegetation

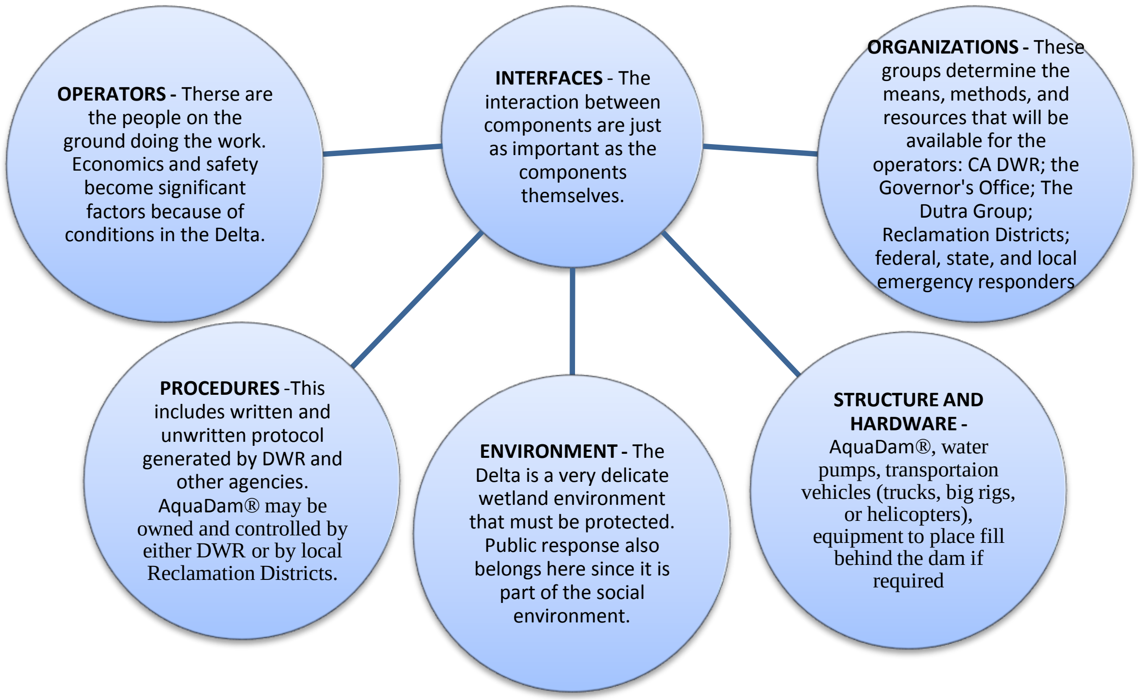

Fig. 6. Components of the proposed sub-system

that will impede the AquaDam®'s effectiveness would be much easier to clear, elevation is clearly evident so the size of the AquaDam® needed can be easily estimated, if implementation occurs just before the breach, crews will not have to worry about moving water, and even if implemented after a breach, there is a good chance it will still be possible to install. For these reasons, the proposed sub-system and the focus of analysis in this paper is an AquaDam® implemented on the land side of a levee. A clear picture of the components of the proposed sub-system can be seen in the flow diagram in Figure 6.

ANALYSES

In order to comprehensively assess the proposed sub-system, a set of criteria was established to identify critical points throughout the evaluation. Background research showed that one of the most significant problems with the current rock system is that the barges will not go near the breach until the water levels out. This means that the flood is allowed to progress to the worst possible scenario before mitigation begins. So the underlying questions throughout this analysis are (a) whether AquaDam® can make up for the rock system's discrepancies and (b) whether AquaDam®'s benefits are worth the cost and effort of implementation.

1. **Economics.** For any project, cost is always one of the most important aspects. For state or district projects, such as levee repair, money is usually raised through taxes, which means the bill is essentially presented to California's residents. Since the state of the California is currently trying to close a budget gap of $25 billion, and most local districts are carrying their own appreciable debt, any action undertaken should endeavor to be as economically efficient as possible, without losing a great amount of effectiveness (Brown and Edmund, 2011).
2. **Structural Soundness.** The levees are already unsound in many areas of the Delta, so if any introduced element compromises the already precarious strength, either mitigating action would be needed or the element should be rejected.
3. **Environmental Impact.** The environmental impact that engineered systems place on the surrounding area, both short- and long-term, is an issue that cannot be ignored. Any potential impact on the environment needs to come with a plan for mitigation.
4. **Speed of Implementation and Accessibility.** A levee breach may start out small, but it will grow exponentially with time. This makes speed of repair a vital factor in choosing an emergency response protocol. This section will also include accessibility factors since many Delta levees will prove difficult for crews to reach.
5. **Policy**. Since most of the levees are owned by state or district entities, legislation may be required to approve and implement an emergency response regimen.

6. **Adverse Conditions**. Conditions found in the Delta region, such as weather and tides, may negatively affect emergency response efforts**.**
7. **Quality and Reliability.** Any proposed component must display characteristics of quality and reliability. Sustainability and resilience will also be analyzed.

These are not the only factors that can be taken into account, but they are arguably the most significant. Although not all are listed explicitly, the sub-system's main components (operators, organizations, hardware, environments, structures, and procedures) and constraints (environmental, political, engineering, operations, construction, and economics) are all accounted for.

EVALUATION

A summary of the evaluation can be found in Table 1.

Economics

Economics is a key component when considering whether the implementation of a new system is feasible. According to Geoff Shaw, who is currently working on a Delta emergency response plan at DWR, the cost of setting up the Rio Vista and Stockton rock stockpiles was approximately $7 million. The scope of this project included: land acquisition, equipment mobilization, site preparation, rock purchases, and construction of any necessary loading and docking infrastructure. However, the cost of setting up these sites pales in comparison to the cost of an emergency response effort. The total for the response to the Jones Tract breach was just under $100 million. Granted, state owned rock stockpiles were not in place at that time and all rock was purchased from The Dutra Group which made it more expensive. Ironically, Jones Tract was only worth approximately $15 million at the time. Thus, the rock system is not very expensive to set up or maintain, but the cost of an emergency response effort can grow rapidly because of the immense amount of labor needed.

The other system examined is the AquaDam® which is made of polyethylene, the most widely used plastic. Compared to rocks, plastic is considerably less expensive and easier to acquire. This significantly lowers the cost of the product. Unit cost varies with size, but an examination will follow of the economic impact of using AquaDam® on Jersey Island. Jersey Island is an average of 10 feet below sea level. Allowing for clearance and room to settle, a 16 foot high AquaDam® (32 feet wide) is probably the best option. (A 14 foot dam would also be adequate, but information for this size is not provided on the standard price list.) This would cost $450-$500 per linear foot. This cost is by no means trivial, since 500 feet of dam would cost $250,000. However, installing an AquaDam® requires very few labor-hours compared to the rock system, so the total cost of an emergency response effort would be much less. Furthermore, AquaDams® can be reused at a later date and multiple uses makes for a better investment.

Structural Soundness

This section will look into the structural soundness of the proposed system. The specific form of AquaDam® under investigation is a three-sided box or half-moon shape on the land side of the levee. The analysis here is used to determine whether this proposed system can sustain the pressure exerted by water. There are two scenarios that we will be studying: (1) the levee is breached and the water has leveled out, and (2) the dam is already in place prior to a levee failure. In the interest of time, new calculations were not performed. Instead the calculations posted by David Doolaege on the AquaDam® website were reviewed and understood. It is these calculations that will be reviewed in this section.

In the first scenario, AquaDam® will be deployed before attempting to drain out the trapped water. There can be two major causes that will lead to a 'failed' system – rolling and slipping. Rolling frequently occurs when the system is unable to resist the water pressure. Due to force imbalance on two sides of the tube, the side that is exposed to the water is likely to be lifted up and thus start rolling. In order to evaluate AquaDam's® resistance to tip over, the moment at the pivot point A (shown in Figure 7) is calculated, assuming that the water-filled tube is rectangular. The two force components that are acting on the tube include the force exerted on the side of the tube that is exposed to the hydrostatic pressure and the weight of the water acting downwards. Each force component contributes to rotating the first water column (on the right hand side).

The sum of the moment at point A can be summarized as follows:

$$\Sigma M_A = W\left(\frac{1}{2}D\right) - F\left(\frac{H}{3}\right) = 0 \qquad \text{(Eq. 1)}$$

W = weight of the water in the tube
D = width of the tube
H = height of the water
F = force being exerted by the hydrostatic pressure

Simplifying the equation, reveals this relationship: D > 0.82(H). This means that if the width of the tube is equal to 0.82 times the water height, the system can achieve a factor safety of 1.0. By varying the dimension of AquaDam®, the system can be manipulated to achieve a desirable factor of safety.

Another failure mode can be the structure sliding along the ground surface. In testing the resistance to slide, it is important to recognize the forces being exerted in the horizontal direction. There are two force components which include the force being exerted by water pressure and static friction. Static friction is in the opposite direction of the applied force, so as long as it is greater than the force of the water, the structure will remain stable. This fact leads to the following equation:

$$\Sigma F = \mu N - F = \mu W - F = 0 \qquad \text{(Eq. 2)}$$

This can also be simplified into μ = 0.5(H/D). The minimum coefficient of friction can be calculated by anticipating the height of the flood water and the corresponding dimensions of the dam. Since sliding depends on various onsite conditions, it's important for the implemented system to have the flexibility to make changes accordingly. Thus, proper site

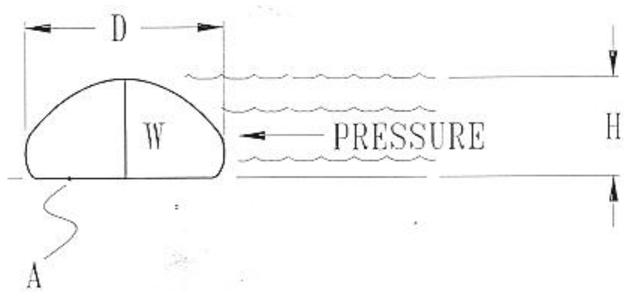

Fig. 7. Forces acting on the AquaDam®

assessment before set-up is essential to determine what dimensions of the dam will be deployed.

The second scenario has the AquaDam® in place before the levee breaches. The biggest concern here is the amount of water that will simultaneously rush against the AquaDam®. Can the AquaDam® withstand a large amount of water if the Delta levee system fails like New Orleans did (850 ft wide levee failed all together)? This question is answered by Professor Seed, an expert in levee systems. He explains that both systems are vulnerable to catastrophic failure. This cannot be prevented. However, levees in the Delta can be looked at as a series system. This means that a stretch of levees is only as strong as its weakest link. Therefore, top priority must be given to the identification of the weakest link in a levee section. Once identified, securing the weakest section with the three-sided box AquaDam® and filling the space between the levee and the dam with water may not only increase the strength of that particular section, but also decrease the exit gradient for the water flow. Ultimately, protecting the weakest link will lead to an increase in the overall reliability of the entire system.

Since a significant length of Delta levees would not fail all at once, there will not be a huge amount of water rushing at the AquaDam® when the levee fails so the only worry is the force from static water. This fact helps to simplify calculations because the force felt in this scenario is essentially identical to the one explained in the first scenario. The water level will slowly rise up as more and more water breaches the levee. Again, by anticipating the depth of the water the necessary dimensions of the dam can be determined.

One stabilizing technique that can be applied to both scenarios is to put piles of soil behind AquaDam®. This simply provides extra weight behind the dam to make it more difficult for it to roll or slide. It will also help in decreasing the amount of seepage beneath the dam. This technique is meant to provide extra support for the overall stability and reliability of the system.

Environmental Impacts

In 2007, EDAW, Inc., an AECOM company, prepared an Initial Study/Mitigated Negative Declaration (IS/MND) for the Delta Emergency Rock and Transfer Facilities Project. It outlined the need and background of the project, related previously in this report, and it reviewed prescribed environmental impacts that could take affect if the project were to be carried out. The report found the following:

1. "The proposed project would have no effects related to Agricultural Resources, Geology and Soils, Hazards and Hazardous Materials, Mineral Resources, Population and Housing, Public Services, or Recreation.
2. The proposed project would have a less-than-significant impact on Aesthetics, Hydrology and Water Quality, Land Use, Transportation/Traffic, and Utilities.
3. The proposed project would have potentially significant impacts related to Air Quality, Biological Resources, Cultural Resources, and Noise, but mitigation measures are proposed that would reduce these effects to less-than-significant levels" (EDAW, 2007).

In order to assess the environmental implications of adding AquaDams® to the system, a partial IS/MND was created which can be found in Appendix B. For the sake of time, the report already generated by EDAW, Inc. was relied upon and details and facts were added where appropriate.

Overall, the AquaDam® has very few environmental impacts. The one that poses the biggest concern and which may require mitigation is noise from the water pumps that will be employed to fill the dam and to pump out any water that splashes over the dam. The other three areas that posed concern for the rock stockpile project (Air Quality, Biological Resources, and Cultural Resources) do not apply to the implementation of the AquaDam®. In addition, the fact that AquaDam® can be deflated, rolled up, and reused at a later date makes it a sustainable flood-fighting tool. From an environmental standpoint, AquaDam® is a very attractive resource.

Speed of Implementation and Accessibility

To analyze speed of implementation and accessibility, a historical slant was taken by looking at the response to the sunny day failure of the Jones Tract levee breach in June 2004. Chuck Walker, Division Manager of Rock Placement with The Dutra Group, was part of the response team and gave some insight into the emergency procedures during that disaster. Walker recalled that one of the biggest challenges in repairing the Jones Tract levee was the tight accessibility which made

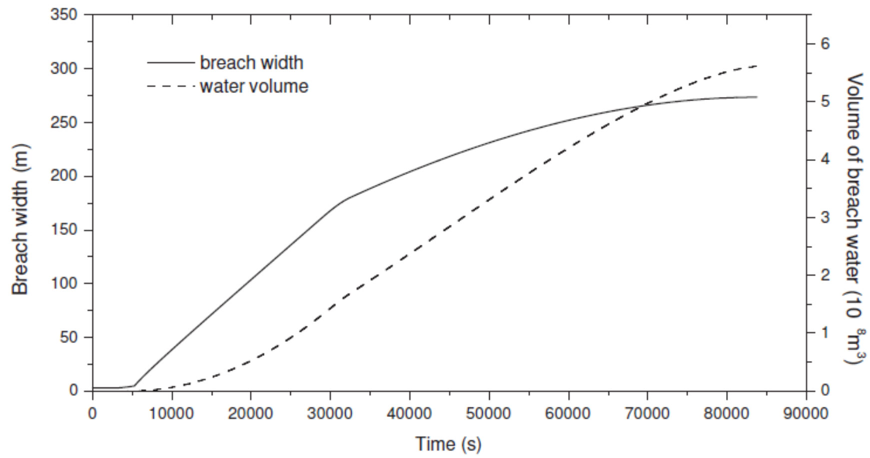

Fig. 8. Model predicted breach width increase and the volume of diverted flood water (Zhu et al, 2007)

navigation of the barges difficult. The Delta levee system becomes twisted and complex in many areas, so this is a problem that can be reasonably predicted for many breach scenarios. Implementation of AquaDam® from the land side may be able to minimize the accessibility issue. In all likelihood, barges will still be needed to transport supplies to repair the levee, but the repair schedule will not be so tight with an AquaDam® in place. So although accessibility might still be a problem, the amount of damage will not be compounded by slow barges.

DWR also compiled an After Action Report (AAR) on the Jones Tract incident (Wegener, 2004). They brought up many points, including: jurisdiction issues, communication barriers (both technical and human), personnel shortages, lack of funding, and obstacles to quick decision-making. The resolution of many of these issues requires a combination of legislation and better planning and operations practices. Incorporating AquaDams® will create the need for additional training of response agencies and their employees. Since lack of training already seems to be an issue, incorporating AquaDam® as a sub-system may further complicate an already complex response system, yet it will not be creating a new problem.

There is one additional point brought up in DWR's AAR that this proposed sub-system will directly address. DWR reported that prepositioned flood fighting materials were depleted during the incident leaving the region even more vulnerable to the next flood until the materials were replaced. The Delta Emergency Rock and Transfer Facilities Project was initiated to solve this problem. The rocks employed in the Jones Tract response were all supplied by The Dutra Group which DWR saw as a weakness, especially when the final cost was tallied. The two project rock stockpiles currently in place are meant to guard against running short of rock again.

However, a situation that involves multiple levee breaches may still require all the rock currently in stockpile and more. If that happens, there are quarries in the area that are ready to increase production if more rock is needed, but a sudden increase in their production rates could create unwanted environmental impacts such as noise and air quality issues. Adding AquaDams® to the rock stockpile system will relieve some of this need, meaning that the stores will last longer and can be more readily available for the next flood.

Speed is of the essence in an emergency response scenario. As previously mentioned, one of the problems with the barge/rock system is that the water is allowed to level out before the barges go anywhere near the breach. This is understandable since no barge intends to end up on the wrong side of a levee. However, it means that the flood always progresses to the worst case possible before mitigation efforts can begin. Once the water is level, the rocks are used to close up the breach as quickly as possible so that the water can be pumped out of the land side.

If an AquaDam® is employed in dry conditions (before a breach), it takes approximately one day to install (for a dam over 10 feet tall). Deployment after a breach occurs will be more difficult so a good estimate for deployment time is unknown. But it will certainly take less than thirty days which is the amount of time it took to close the Jones Tract breach. Breaches grow very quickly. A study done on clay dikes resulted in an analytical model for the growth rate of a levee breach (Zhu et al, 2007). An example of the model's output can be seen through a prediction of the failure of the Xiguan Polder on the Yangtze River (Figure 8). The graph shows that at approximately 30,000 seconds (just over eight hours), the breach exceeds 150 meters (500 feet). If a response team is looking to implement a flood fighting tool before the breach reaches an unmanageable size, they must act quickly.

Therefore, for an AquaDam® to be effective, the breach must be detected quickly and the AquaDam® deployed soon thereafter. The current method for breach detection is by sight. While this may be the most effective method for places like Jersey Island where levee patrols are constant, it is insufficient for the levees that are monitored infrequently and irregularly.

For example, the exact start time of the Jones Tract breach is unknown since it was not detected by levee officials, but by a passing boat. Unfortunately, with the time constraint on this research project, investigation into a breach detection system is outside the scope of this report.

Assuming a breach or even a weakened section of levee is detected early, implementation of an AquaDam® must happen instantaneously. An AquaDam® with up to 80,000 gallons of water storage (roughly equal to a dam that is 10 feet high, 20 feet wide, and 100 feet long) can be loaded into the back of a standard pick-up truck. Transportation for anything bigger can be loaded, with forklifts, into the back of a big rig. Either operation can be done quickly, especially if communication is good and everyone involved knows the location of the AquaDam® and proper procedure. Efficient distribution of information is key in an emergency response. Deployment and installation of an AquaDam® can be very quick, even after accounting for loading and transport procedures.

Another option for deployment is air transport. A prominent image of the Hurricane Katrina disaster was National Guard helicopters bombing sandbags in order to plug the levee breach. Lieutenant Martin at the California National Guard headquarters in Sacramento was able to provide more information on the process and timeline for calling in the National Guard during an emergency. Once a disaster occurs, the order calling up the National Guard comes from the California Governor's office by way of the California Emergency Management Agency (Cal EMA). Even before the official order comes through, Cal EMA may give the National Guard an alert order. For example, an alert order may be issued immediately after an earthquake. As soon as the National Guard receives the alert order, they require their soldiers to report to base within 48 hours. The alert order is critical in getting the National Guard ready and moving, even prior to receiving the official order.

Although the National Guard takes a minimum of 48 hours to respond, helicopters can be extremely useful in deploying AquaDams®, particularly to locations that are difficult to reach by land or water. Blackhawk helicopters, standard in the Army, can lift up to 9,000 pounds which makes them more than capable of transporting AquaDams®. However, helicopters will take an additional amount of coordination. There will need to be AquaDams® ready to go near an airfield and the National Guard will have to be informed of this location. Coordination like this between the different agencies involved is a very important part of an emergency response plan. Again due to time restraints, research to explore the communications aspect in further detail was not possible.

Policy

After the Jones Tract breach and Hurricane Katrina, a flurry of political action was taken regarding the California Delta. Executive Order S-17-06 was signed in 2006 by Governor Schwarzenegger to "develop a durable vision for sustainable management of the Delta" by establishing a Blue Ribbon Task Force – a group gathered to solve and/or advise on the Delta (Fact Sheet, 2010). Before the Blue Ribbon Task Force finalized their report in November 2007, the Department of Water Resources completed an Interim Delta Emergency Operations (EOP) Concept Paper in April 2007.

The Interim Delta EOP Concept Paper was meant to (a) summarize DWR's role and responsibilities during an emergency, (b) serve as a primer on how DWR would handle Delta flood emergencies, and (c) be easily updated as new needs and response techniques developed (EOP Goals, 2010). This concept paper was part of the foundational groundwork of the Enhanced Delta Emergency Response. Through the EOP, "procedures for emergency preparedness and incident management…[will] enhance the State's ability to prepare for, respond to and recover from a Delta levee failure disaster" (DWR, 2007).

In order to develop the EOP, two phases were set:

1. Conduct a discovery process to analyze previously developed plans and procedures and identify current DWR capabilities for response to emergencies in the Delta. Response actions that can be take to reduce the impact of a Delta levee failure will then be categorized.
2. Engage partners in local, state, and federal government, as well as the private sector, to develop an EOP for responding to levee failure events, stabilizing the system and facilitating the recovery process while being consistent and compliant with California's Standardized Emergency Management Systems (SEMS) and the National Incident Management System (NIMS).

In a "typical flood emergency," at the federal level, DWR works with the US Bureau of Reclamation, US Army Corps of Engineers, and US Geological Survey. At the state level they work with the Office of Emergency Service, California Department of Forestry and Fire Protection, California Conservation Corps and the California National Guard. At the local level, DWR works with Levee Maintaining Agencies, Operational Areas and other agencies (DWR, 2007). Strong lines of communication are critical during any disaster, especially with approximately fifty agencies involved in the response effort.

There is a process that DWR follows in completing the EOP. First, they complete an Interim Emergency Operations Plan which is presented to public stake holders interested in the Delta. From there, DWR completes multiple phases of engineering design work. For the Delta Emergency Rock and Transfer Facilities Project, these phases included:

1. Developing preliminary plans to determine quantity and gradation of rock needed to repair multiple levee breaches and block eight river channels in order to minimize the intrusion of salinity in the interior of the Delta
2. Securing three new joint stockpile/ transfer facilities with close proximity to trouble spots in the Delta and easy access to Federal and State highways
3. Completing design requirements and contracting for construction of a belt conveyer system capable of moving large quantities of large diameter rock necessary to close levee breaches and construct temporary barriers

Criteria	Rock Stockpiles (current system)	Rock Stockpiles with AquaDam® (proposed sub-system)
Economics	This system is already in place so the upfront cost is sunk. However, the cost of implementing a response is still significant.	AquaDam® has a substantial upfront cost but the cost of an emergency response effort is significantly less since fewer labor-hours are necessary.
Structural Soundness	The overall strength of the Delta levees is poor. However, as evident on Jersey Island, restoration and strengthening of the levees is on-going, although still incomplete and somewhat inconsistent.	As long as the proper dimensions are chosen, AquaDam® is engineered to withstand failure from rolling or sliding. Steps can be taken, such as putting fill behind the dam, to increase reliability.
Environmental Impacts	Any significant environmental impact is reduced to less-than-significant with mitigation efforts.	AquaDam® has a minimal effect on the surrounding environment. Noise from the water pumps is the biggest concern. After an AquaDam® has served its purpose, it can be deflated, rolled up, and reused at a later time.
Accessibility and Speed of Implementation	Accessibility was an issue during the 2004 Jones Tract response effort and it could be an issue again depending on where the next breach occurs. Rocks are not employed until after the water has leveled, which means that flooding always reaches the worst case possible.	If the breach is detected early on, AquaDam® may be used effectively to halt the flood waters. Although AquaDam® can take less than a day to implement, the timing may still be problematic since breaches grow exponentially.
Policy	The policy for this system is already in place, although it is unclear whether some of the policy issues identified after the Jones Tract failure have been rectified.	In order to approve the amendment to the emergency project, DWR will need to obtain funds to set-up infrastructure.
Adverse Conditions	Barges and boats can be affected.	If implemented on the land side of the levee, the AquaDam® will be shielded from many of the more stringent conditions the Delta presents. It will not be feasible to implement AquaDam® on the water side of a levee.
Quality and Reliability	The rocks are considered to be a proven system, but they do not meet all the standards of quality and reliability.	AquaDam® will most likely satisfy all characteristics associated with quality, but there is uncertainty inherent in the fact that no field testing was done in the course of this report.

Table 1. Evaluation Summary

4. Establishing new procurement contracts for rock to be placed at three stockpile/transfer facilities and include contingency based arrangements for contractors to place rock in event of an emergency

In order to implement a new system (or sub-system), the 2010 Delta EOP can be used since it reflects DWR's current ability to respond to a levee breach. The most difficult part will be to convince policy makers of the engineering capabilities of the system. While consulting with David Mraz of DWR, he was unconvinced that the tube system or the AquaDam® would work. The rock system has been proven to show over the last 30 to 40 years that it can work to prevent a wide-scale levee breach. Technologies that have yet to be tested in the Delta region are a much bigger risk. Convincing policy makers would require a presentation that describes the process of the new technology and multiple demonstrations that the new system will perform well in the Delta. Essentially, in order for the new system to be implemented, DWR Engineers will need to be convinced that the system will work and they in turn must convince policy makers that funding the project is worthwhile.

Adverse Conditions

Since the Delta is a marine environment, there are many conditions that can adversely impact an emergency response effort. The current response system relies entirely on barges, so bad weather or high tides can make accessing the disaster site difficult and possibly treacherous. Weather and tides can also make it much more difficult to place the rocks or other flood fighting materials. It is partly because of these adverse conditions that the idea of implementing an AquaDam® on the water side of a levee was rejected and the focus shifted to land side operations. Although installation videos on the AquaDam® website demonstrate how to deploy an AquaDam® in moving water, the conditions in the video are minimal compared to what is found every day in the Delta. Making the extra effort to deploy on the water side would also take much longer than deployment on the land side and it has been previously established that time is a critical factor in the response process.

What is not clear through research is whether deploying an AquaDam® on the land side would even be possible if the levee has already breached and water is rushing through. Installation of the AquaDam® is a very hands-on operation so if it is unsafe for workers to stand in the rushing water, then operations must be halted. This points to the fact that in this application, environmental conditions are very closely tied to ergonomics. AquaDam® is reportedly easy to install with only a few workers, assuming the environmental conditions are fair. If there is high wind, heavy rain, or rushing water, workers may find it extremely difficult and dangerous to deploy the dam.

Quality and Reliability

Quality is defined as satisfying these four characteristics: serviceability, safety, compatibility, and durability. AquaDam® serves its purpose by preventing flooding in the event of a levee breach. Safety may come into question during installation procedures, but once the dam is deployed, it is a very stable structure and can even be used as a work platform. As shown in the environmental section, AquaDam® is very compatible with the surrounding landscape and wildlife. Durability, arguably the most important of the four characteristics, can also be achieved by AquaDam®, although for a limited period of time. On his website, Doolaege claims that AquaDam® can safely stay in use for up to a year. It can be patched or repaired in place if issues arise. A broken levee should be repaired in well under a year, but the limited lifespan of AquaDam® may still be cause for concern in this respect.

Reliability is defined as the likelihood that a given system or component will develop quality. It is estimated that an AquaDam® will have a high probability of achieving quality. However, there is substantial uncertainty arising from the fact that this research lacks field tests. It can be theorized that the AquaDam® will perform well in the Delta environment, but there is no testing to prove this theory.

An important aspect associated with quality and reliability is a life cycle assessment. The life cycle assessment of the AquaDam® proves it to be environmentally safe and sustainable. AquaDams® are made of two polyethylene liners contained by a single woven geotech outer tube. The processing of polyethylene and the geotech outer tube is done with natural gas and benzene or other resin polymers. The plastics can be from post-consumer products, hence the geotech materials can be made from recycled plastics. These plastics take a very long time to degrade, so properly disposing of the material after its use is necessary. One of the benefits and advantages of the AquaDam® is that it is reusable. After the AquaDam® has served its purpose, it can be drained of the water, folded and stored away for another time. This process increases its life cycle and allows owners to use the AquaDam® for many years to come. Polyethylene and other geotech materials are very sturdy and reliable and will not break easily. They are suitable for use in very harsh conditions.

Results from the Physical Model

The physical model associated with this project is an attempt to reaffirm the principles behind how the AquaDam® works. Many simplifications were made during the design and construction of this model. Instead of clay and soil, cardboard, duck tape, and a water-tight sealant are used to create the "levee." Long, water-filled balloons are used to simulate an AquaDam®.

Just from looking at the materials list, it is apparent that the model is an extremely limited version of a Delta levee. The model does not have wind, waves, and debris unceasingly battering against it. Thus, this report did not rely heavily on the physical model when drawing a conclusion. However, the model does help to understand the principles on which AquaDam® is based. After a few iterations of running water through the levee breach, it is clear that two balloons lying together (like an AquaDam®) is much more stable than one balloon by itself (like the tube). In that sense, the model did confirm that AquaDam® is a superior choice to the tube.

CONCLUSION

Although the current rock system is a proven technology, it has some serious drawbacks. These drawbacks were serious enough to prompt an examination of alternative or supplementary tools for fighting floods due to a levee breach. The most significant of these issues is that barging operations cannot begin until the water has leveled out. Because of this delay, the flood is allowed to progress to the worst possible scenario. Once the water has leveled, the rocks are deployed as quickly as possible to close the breach so that the water can be pumped out of the land side without leaching too much salinity into the soil.

The goal in undertaking this research project was to examine new flood fighting technologies to see if any could be used to mitigate the problems with the current rock system. Two different technologies were explored: the tube and AquaDam®. The tube did not merit further examination for a number of reasons. Foremost was the difficulty of deploying the tube in Delta conditions. It would most likely need supplementary infrastructure to keep it in place. Although very similar to the tube in methodology (both use the weight of water to stabilize their structure), AquaDam® proved more promising upon preliminary investigations, so that is the technology that was analyzed further.

Implementing AquaDam® on the water side of a levee breach would be just as infeasible as implementing the tube. The conditions in the Delta are simply too fierce to allow for such operations. However, implementing AquaDam® on the land side of a breach shows promise. It avoids many of the implementation issues inherent in water side operations. If installation is initiated quickly, emergency responders may be able to halt flood water before it can do the maximum amount of damage. Even if implementation is not possible until the water has leveled out, AquaDam® can be installed more quickly than a rock barricade, so the water on the land side can be pumped out much sooner.

However, there are many uncertainties included in this research. Theoretically, AquaDam® can withstand conditions found in the Delta, but without a more adequate physical model or field tests, this result lacks conviction. The bottom line is that AquaDam® and other technologies like it merit attention from flood fighting agencies. The current system may be proven, but that does not mean it is the final solution to the problem.

Ever Forward

After new technologies have been tested and proven, a comprehensive technology delivery system (TDS) is needed to distribute pertinent information. A TDS needs to address the government, public, environment and commerce and industry. This report addresses the government and legislation under the policy section. Implementation of a new system can be achieved by following similar steps taken to implement the rock stockpiles. Perhaps what is unclear is how to distribute information to the general public. Also, how will public opinion be heard and assimilated? Given that a new system is feasible, the same steps that DWR took in implementing the rock stockpile project could be taken to communicate information regarding new systems and technologies. They first released an initial draft of the plan and invited the public to comment with questions or concerns. These comments can then be incorporated before the final implementation. Part of the TDS would be to review and evaluate approximately every five years to make sure that the public still finds the system useful and that it has been employed in a way that does not create more negative impacts than initially predicted. Regardless of public sentiment, such a review would ensure that the system continues to stay in line with its original goals.

The environment has already been addressed in this report through a Mitigated Negative Declaration in the evaluation section. The only impact that will require action is the noise generated by the water pumps. However, the environment in the Delta is very delicate and complex. Input from biologists and wildlife specialists will be beneficial for validating (or disputing) these claims.

Lastly, commerce and industry have a very large stake in the health of the Delta system since its demise would impact many aspects of California's economy. New technologies, like AquaDam®, can be a very rewarding investment if they are successful in preventing large floods in the Delta region.

One of the main targets in dispersing information about new technologies will be the Reclamation Districts and people like Tom Williams of the Ironhouse Sanitary District who are charged with the upkeep of certain sections of levee. For example, Tom Williams might have greatly benefited from the implementation of an AquaDam® during the storm of 2005-2006. A breach on Jersey Island during that storm was prevented by reinforcing the levees with rock, but there was a point where Williams was not sure the repair effort would be enough. Had an AquaDam® been at Williams's disposal, he might have deployed it in a large half-moon around the compromised section of levee so that if the breach did occur, the water would not have been allowed to spread very far. So while a main focus of this TDS is larger agencies like DWR and the Delta Stewardship Council, smaller agencies, like the Ironhouse Sanitary District, will also be targeted since they may greatly benefit from new technology.

Moving forward with research, there exist several other projects complementary to this one. In particular, there are two that merit considerable attention. The first is to examine the infrastructure in place that detects levee breaches. Efficient detection is the first step in an effective levee breach response system. The fact that nobody even knows the start time of the Jones Tract levee breach is a strong sign that the current detection system needs help.

Second, a comprehensive emergency communications plan is needed. It is not enough to just assume that all agencies will report to DWR for instruction in an emergency situation. Again going back to the Jones Tract After Action Report, numerous communication issues were sited, including the fact that the location of the remote command center was unknown to many for the first day of emergency operations.

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