Composite Risk Assessment for the Sacramento–San Joaquin Delta Levee System

William H. McAnally, P.E., F.ASCE[1]; Christopher M. Wallen, P.G.[2]; Steven C. Sanborn, P.E., M.ASCE[3]; and Eugene C. Maak, P.E., M.ASCE[4]

Abstract: The objectives of this project were to analyze available Sacramento–San Joaquin Delta, California, levee risk information in a Composite Risk Management matrix and examine the results for management decision support. U.S. Army Corps of Engineers (USACE) guidance documents define risk as the "probability and severity of loss linked to hazards" and prescribe a composite risk assessment method. The Delta Risk Management Strategy performed for a group of state and federal partners provided analyses of the relative probability of hazards and severity of risks in the Delta and provide the information needed for a risk analysis compliant with USACE requirements. Composite Risk assessment provides rank-ordered lists of the highest risk zones–those with the greatest probability of failure combined with the most severe consequences–for several hundred protected areas in the Delta. Although uncertainties in the absolute magnitude of the results make them most useful for comparisons, the actual values of the probabilities and consequences are alarming. For example, Sargent Barnhart Tract, northwest of Stockton, has a mean annual failure rate of 0.07, or an expected levee failure every 14 years, with a probable 96 fatalities for a nighttime seismic-induced failure. Adjacent tracts with only slightly lower failure probabilities put another 500 lives at risk. An area of the Suisun Marsh has a projected failure rate of 0.5, or once every two years, with maximum possible damages exceeding $250 million. The Sacramento Pocket Area, with a mean annual failure rate of 0.006, has over $9 billion at risk. Although refinements to these risk estimates are possible, this paper and the Delta Risk Management Strategy analyses provide more than sufficient evidence that flooding in the Sacramento–San Joaquin Delta presents significant risks to California and the nation. Hundreds of lives and billions of dollar damages are at risk. Urgent action is necessary to manage those risks. **DOI:** 10.1061/(ASCE)WR.1943-5452.0000362. © *2014 American Society of Civil Engineers.*

Author keywords: Risk; Levee; Flooding; California; Sacramento River; San Joaquin River.

Introduction

The objectives of the work described here were to analyze available Sacramento–San Joaquin Delta levee risk information in a composite risk management (CRM) matrix and examine the results for management decision support.

The Sacramento–San Joaquin Delta (see Fig. 1) is a vital economic and ecologic resource for the residents of California and the nation. Delta water supports $400 billon of the state economy, supplies two-thirds of the households, and provides habitat for many species.

The Delta consists of a 700-mile network of controlled channels, 1,800 km of levees (600 km of which are federally managed), and 70-plus islands, most of which are well below sea level. The current system is a patchwork of projects implemented over the last 150 years for primarily land reclamation, flood control, navigation, and water delivery. The levees are aging and threatened by multiple potential failure causes, including seismic motion and overtopping erosion.

Deep-water shipping channels connect San Francisco bay to the ports of Stockton and Sacramento. Water is directed through the Delta to export stations at the southern edge. Thousands of km of roads and utilities traverse the channels and islands. Small agrarian and tourist towns are scattered across the Delta landscape. Marinas and houses line portions of the land sides of the levees and recreational users employ the Delta's land and water resources. The Delta's infrastructure and ecosystem are highly stressed and continuing development, subsidence, invasive species, seismic risk, and weather/climate risks will challenge the system even further in the future.

The U.S. Army Corps of Engineers (USACE) supported the joint state-federal Delta Risk Management Strategy (DRMS) effort that has produced detailed reports on risks and risk management for the Sacramento–San Joaquin Delta (URS/JBA 2008, 2011). Those documents provide information on property damage and potential life loss from flooding, but do not present the information in CRM assessment form as required for USACE risk assessments.

Risk Assessment and Management

USACE Definitions

Army Field Manual 5-19, *Composite Risk Management* (U.S. Army 2006) defines risk as: "probability and severity of loss linked to hazards." This definition is consistent with present professional

[1]Engineer, Dynamic Solutions, LLC, and Research Professor, Mississippi State Univ., 486 Sagamore Cir, Columbus, MS, 39705 (corresponding author). E-mail: mcanally@gmail.com

[2]Vice President, Dynamic Solutions, Limited Liability Corporation (LLC), 6241 Deane Hill Dr., Knoxville, TN, 37919.

[3]Engineer, Dynamic Solutions, Limited Liability Corporation (LLC), 6241 Deane Hill Dr., Knoxville, TN, 37919.

[4]Engineer, U.S. Army Corps of Engineers, Sacramento District, 1325 J St., Sacramento, CA 95814.

Note. This manuscript was submitted on May 31, 2012; approved on February 19, 2013; published online on February 21, 2013. Discussion period open until October 1, 2014; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Water Resources Planning and Management***, Vol. 140, No. 5, May 1, 2014. © ASCE, ISSN 0733-9496/2014/5-734-743/$25.00.

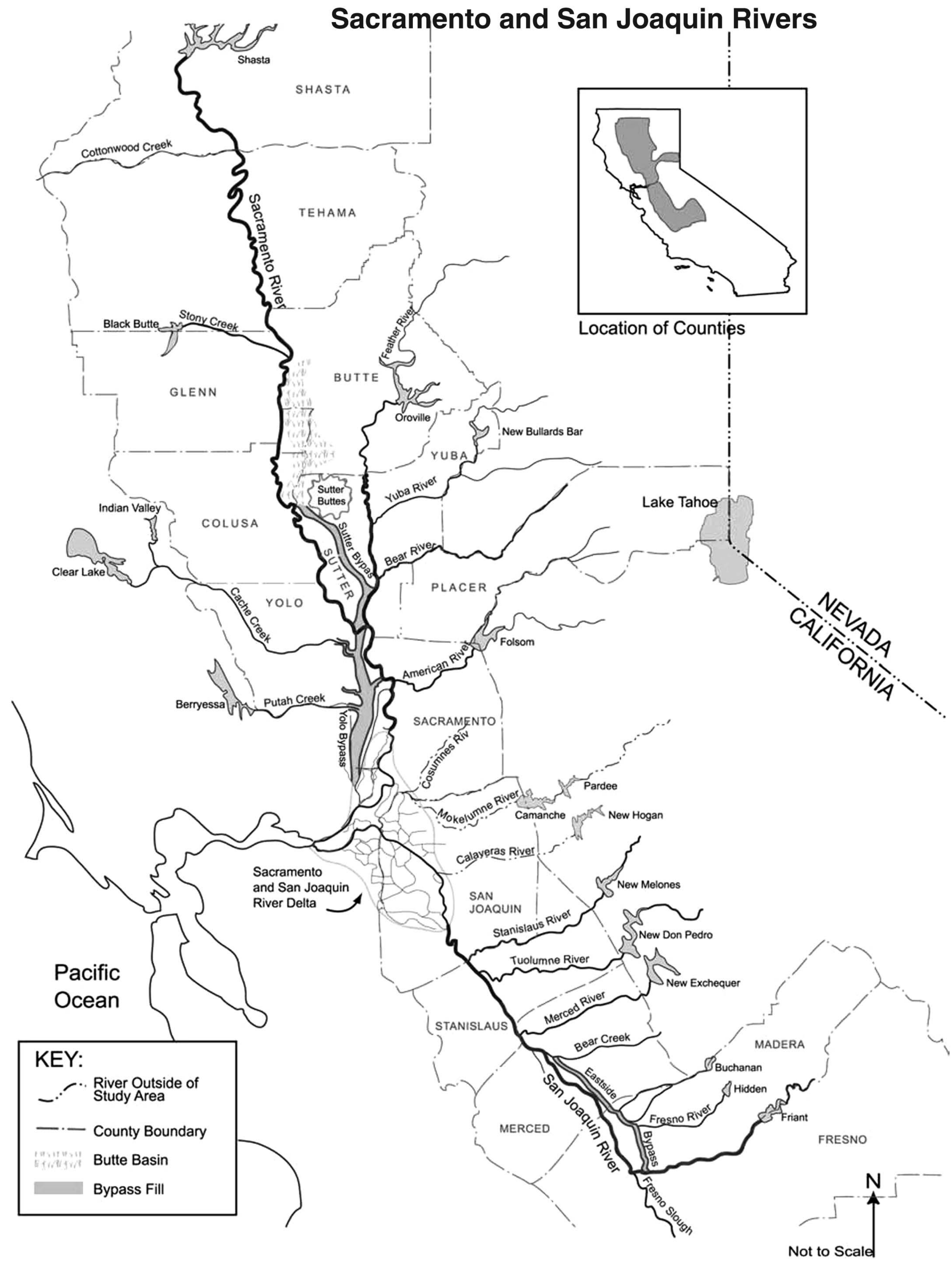

Fig. 1. Sacramento and San Joaquin River basins (reprinted from USACE 2002)

J. Water Resour. Plann. Manage., 2014, 140(5): 734-743

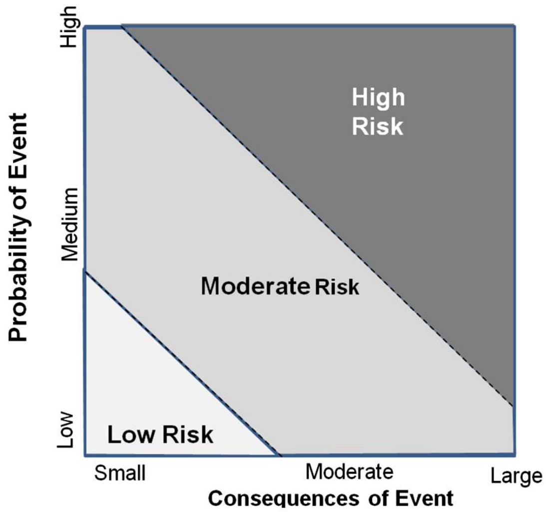

Fig. 2. Illustration of the combined effects of event probability and event consequences in assigning risk levels

practice in risk management (e.g., NRC 2007; ISO 2009) that recognizes two distinct components in risk–the probability of an event and the magnitude of consequences from that event.

The role of the two factors–probability of an event and the consequences of that event–in defining risk can be illustrated as in Fig. 2. The vertical axis represents the probability of an event, ranging from very low, such a 500-year return period storm, to a rather high probability, such as an annual spring runoff event. The horizontal axis represents the consequences of the event–low consequences might include small economic damages, whereas high consequences may include loss of human life. The diagram can be categorized into low, medium and high risk zones, as shown in Fig. 2, with the actual delineations among them depending on a careful analysis of the specific system.

The USACE Risk Management Gateway provides a detailed, descriptive definition of risk assessment, summarize as: Risk assessment is a systematic, evidence-based approach for describing the likelihood and consequences of any action, which is a small part of the bigger process called risk management (USACE 2011a). Field Manual 5-19 (U.S. Army 2006) defines risk management as 'the process of identifying, assessing, and controlling risks arising from operational factors and making decisions that balance risk cost with mission benefits." CRM is defined as the process of identifying, assessing, and controlling risks arising from all causes by making decisions that balance risk with benefits. These definitions, although expressed in terms pertinent to the Army and USACE, are consistent with professional practice as defined by the National Research Council (NRC 2007) and International Standards Organization (ISO 2009).

Probability in Risk Management

Probability of an event and of the resulting consequences includes multiple sources of uncertainty, which the USACE (1996) categorizes as: knowledge of future events, use of simplified models, economic and social information, and project feature performance. Engineer Circular EC 1110-2-6067 (USACE 2010) defines uncertainty in National Flood Insurance Program levee evaluations as, "a measure of the imprecision of knowledge of variables and functions used in the risk analysis," which is used here.

Consequences in Risk Management

Federal agencies, including the USACE, typically evaluate economic, human health and life, and environmental consequences separately. Attempts to address health and life losses quantitatively are often controversial and encounter the challenge that human life is priceless. Recently, environmental consequences have proved susceptible to quantification through ecosystem services analyses, but the field is still developing.

Among Federal agencies, the EPA has attempted to use the *Value of a Statistical Life* to define the cost-benefit ratio for regulations (EPA 2011) arriving at a value of $7.4M in 2006 dollars. The agency plans to change over to a *Value of Mortality Risk* in the future to reduce controversy. Other agencies have used the *Cost to Save a Statistical Life* as an alternative.

Recent efforts by USACE to formulate new dam and levee risk assessment strategies and the ongoing process to revise the Federal *Principles and Practices* may produce quantitative expressions for human health and safety and environmental quality. However, existing USACE guidance does not provide a mechanism for doing so. Separate risk assessments are the norm for economics, human health and life, and environmental quality, including ecosystem components.

Composite Risk Management Process

Field Manual 5-19 provides guidance on applying CRM through a five-step process depicted in Fig. 3. Whereas the Manual explains the five steps in terms of military personnel and missions, e.g., "The factors of mission, enemy, terrain and weather, troops and support available, time available, and civil considerations (METT-TC) serve as a standard format for identification of hazards, on-duty or off-duty," those terms have equivalent civil works factor connotations:

- Mission: Project purpose, operation and maintenance;
- Enemy: Vandals, terrorists, earthquakes, floods;
- Terrain and weather: Natural factors such as soil, water, weather, and animals;
- Troops and support: USACE, local sponsors, stakeholders;
- Time available: Time and budget constraints; and
- Civil considerations: For example, nonproject activities such as recreation, farming.

Once hazards have been identified, step 2 in the CRM is to assess each hazard by three substeps:

- Assess the probability of the event or occurrence.
- Estimate the expected result or severity of an event or occurrence.
- Determine the specified level of risk for a given probability and severity using the standard risk assessment matrix.

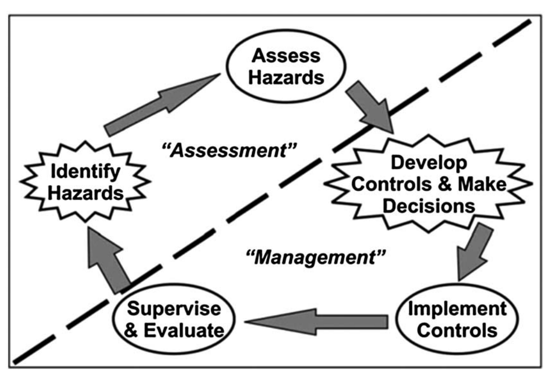

Fig. 3. CRM steps (U.S. Army 2006)

J. Water Resour. Plann. Manage., 2014, 140(5): 734-743

Table 1. CRM Hazard Assessment Matrix (U.S. Army 2006)

Risk assessment matrix						
		Probability				
Severity		Frequent	Likely	Occasional	Seldom	Unlikely
Catastrophic	I	*E*	*E*	*H*	*H*	*M*
Critical	II	*E*	*H*	*H*	*M*	*L*
Marginal	III	*H*	*M*	*M*	*L*	*L*
Negligible	IV	*M*	*L*	*L*	*L*	*L*

Note: *E* = Extremely high; *H* = High; *L* = Low; *M* = Moderate.

Fig. 3 shows that the risk management steps following hazard assessment are:

- Develop controls and make decisions;
- Implement controls; and
- Supervise and evaluate.

Fig. 3 also indicates that the steps repeat, with the focus on *residual risk* in the next hazard identification step. The latter two bullets can be recognized as steps in an adaptive management approach, which the NRC (NRC 2009) describes as, "Flexible decision making that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better understood."

Table 1 shows the Field Manual's Risk Assessment Matrix. It reflects the two components of risk as shown in Fig. 2–probability of occurrence and severity of consequences. Probability of occurrence is expressed as one of five categories ranging from *Frequent* to *Unlikely* and severity of consequences is expressed as one of four categories ranging from *Negligible* to *Catastrophic*. The Manual explains these categories in primarily military terms; nevertheless, the concepts are still applicable to civil works activities with suitable translation.

The CRM matrix in Table 1 expresses composite risk in four levels:

1. Extremely high risk: Loss of ability to accomplish the mission if hazards occur during mission.
2. High risk: Significant degradation of mission capabilities in terms of the required mission standard, inability to accomplish all parts of the mission, or inability to complete the mission to standard if hazards occur during the mission.
3. Moderate risk: Expected degraded mission capabilities in terms of the required mission standard and will result in reduced mission capability if hazards occur during mission.
4. Low risk: Expected losses have little or no impact on accomplishing the mission.

Of particular note is that the Manual-delineated process does not explicitly combine the hazards in a single composite risk evaluation. Each hazard is assessed and managed individually, as if it were uncorrelated with any other hazard. It is the responsibility of the risk manager to understand how the hazards may interact to create a higher risk.

Using the risk assessment matrix is the key guidance provided by Field Manual 5-19, but its implementation for civil works activities diverges from the military-centric procedures and examples given in the Manual. Other USACE guidance describes the process for performing composite risk management in civil works.

Risk values used to populate a risk matrix can be simple designations of high, medium, and low as shown in Tables 1 and 2, or nondimensional numeric values calculated by a risk assessment procedure. They can be expressed mathematically as a simple product

Table 2. Matrix Risk Levels

Risk level key
5. Highest
4. Higher
3. High
2. Lower
1. Lowest

$$\text{Risk index} = \frac{P[\text{Event}] * (\text{consequences of event})}{\text{Normalizing value}} \quad (1)$$

where the *Normalizing Value* is selected to remove units from the index and fit it to a certain range, such as 0–1, or 1–100, and $P[\,]$ = probability function of the random variable within the brackets.

In toxic materials and security risk analyses the $P[\text{Event}]$ is often defined as

$$P[\text{Event}] = P[\text{Threat}] * [\text{Vulnerability to threat}] \quad (2)$$

USACE (2011b) develops risk indexes using the sum:

$$\text{Risk Index} = \beta_{\text{CI}} + \beta_{\text{RL}} \quad (3)$$

where β_{CI} = index value ranging from 10 (high likelihood of failure) to 0 (low likelihood of failure) from a lookup table corresponding to machinery condition indexes ranging from 0 (poor) to 10 (Good) and β_{RL} = index value ranging from 1 (minor revenue loss) to 10 (high revenue loss). The results are the index values ranging from 1 (low risk) to 20 (high risk) and the diagonal division into four risk categories.

Engineer Circular 1110-2-6062 (USACE 2011b) applies a more detailed analysis to an example dam breach problem, defining the risk as

$$R = HP[F]P[E]XL \quad (4)$$

where R = risk in expected losses per year; H = number of expected events per year; $P[F]$ = probability of failure of a project feature for each event; $P[E]$ = probability of a breach, given event and feature failure; X = conditional exposure of people or property caused by the event; and L = loss rate for the exposed people and property.

Whereas these mathematical forms are useful in understanding the interactions and separating high risk from low risk, risk values are not typically treated as precise magnitudes. They are more often scaled to a linear relationship appropriate for assigning classes of risk as displayed in Figs. 2 and 3 and shown in Eq. (1).

These examples serve to illustrate the variety of ways risk can be estimated and expressed. Other than the overall approach, the conceptual form of the risk matrix, and requirement for sound analyses, USACE risk assessment has considerable latitude. In the words of Field Manual 5-19: "Technical competency, operational experience, and lessons-learned weigh higher than any set of alphanumeric codes. Mathematics and matrixes are not a substitute for sound judgment" (U.S. Army 2006).

Delta Risk Management Strategy

The California Department of Water Resources commissioned the Delta Risk Management Study (DRMS) on behalf of the CALFED agencies–more than 20 state and Federal organizations with resource management responsibilities in the Sacramento–San Joaquin Delta. The purposes of the DRMS Phase 1 were to: "… assess expected performance of Delta and Suisun Marsh

J. Water Resour. Plann. Manage., 2014, 140(5): 734-743

levees (under various stressors and hazards) and the potential economic, environmental, and public health and safety consequences of levee failures to the Delta region and to California as a whole" (URS/JBA 2008).

The DRMS Phase 1 report was published (still labeled as a draft) in October 2008, following a final revision in response to reviews by a panel of independent peer reviewers. Those documents (URS/JBA 2008; CALFED Science Program Independent Review Panel 2008) are used here for the DRMS Phase 1 findings.

DRMS Hazards and Assessment Methods

DRMS evaluated three hazard categories as potential threats to Delta and Suisun levees:

- Seismic events
- Hydrologic events (floods)
- Normal events (*aka* sunny day failures)

Seismic events were expressed as the probability of a given ground motion in each area of the Delta for an earthquake of a given type and magnitude on a given fault. Flood events were expressed in terms of a combined probability of water level occurrence, given: (1) inflows from all streams using a Log-Pearson Type III distribution of historical flows plus the predicted change in flow probabilities arising from climate change; and (2) tidal elevation probabilities from historical gaged water level stations adjusted for projected sea level rise. Normal events included nonseismic, nonflood events, such as those precipitated by high tides and rodent damage. Sea level change and climate change were considered to be part of the Delta environment (i.e., not hazards), with an associated probability for each in a given year [2005 (base year), 2050, and 2100]. Detailed zone-by-zone analysis was performed for 2005 conditions. For future conditions, analyses predicted the overall changes of risk for the Delta.

For each category the threat was quantified in terms of a *Hazard Analysis* or probability of occurrence [P[threat] in Eq. (3)] and a *Levee Vulnerability Analysis* that produced the conditional probability of failure for a levee. A *System Model* was used to evaluate the combination of events and levee damage for a number of threat scenarios.

The System Model considered the combination of a hazard and levee vulnerability to have three possible levee outcomes– No Damage, Damage without Breaching, and Breaching. The latter two were assumed to constitute events with consequences– Emergency Response costs for Damage without Breaching and all assumed consequences for Breaching. The result was a tree-structure sequence of events and consequences.

DRMS Consequences and Assessment Methods

Consequences of levee failures and subsequent flooding were considered in three main categories:

- Life safety
- Water quality
- Economic

Consequences were evaluated quantitatively where possible and qualitatively otherwise. They were also evaluated on a per-island and Delta/state-wide basis. Per-island economic consequences were evaluated for 182 individual zones–islands and a few nonisland areas adjacent to the levees–for life loss and damage costs specific to those zones. Delta-wide and state-wide consequences were presented for scenarios of 1–50 islands experiencing levee failure. An ecosystem consequences task was performed during the DRMS work, but was not published in the final documents.

Life safety impacts were evaluated for life-loss probability using a simplified form of the LIFESim model (Aboelata et al. 2003) which considered six scenarios of flood, seismic, and sunny day failures during daytime and nighttime through evaluations of:

- Flood routing
- Population exposure
- Warning and evacuation

The System Model assessed the potential for events that would damage the levees and included uncertainty for natural variability (aleatory uncertainty) and for limited knowledge (epistemic uncertainty).

The analysis showed that 10 zones had at least a 10 percent probability of 100 deaths or more if a breach occurred in their protecting levees:

- *57_124*
- Lincoln_Village_Tract
- Sacramento_Pocket_Area
- Sargent_Barnhart_Tract 2
- Sargent_Barnhart_Tract 2
- Shima_Tract
- Smith_Tract
- West Sacramento North
- *Zone 158*
- *Zone 185*

Another twenty-six zones had at least a 10 percent probability of 10 deaths or more if a breach occurred. Sensitivity tests indicated that the above probabilities could be two to five times higher or lower, depending on the validity of assumptions in the analysis. Despite this wide range, the results are useful in ranking the *relative* probability of adverse consequences among islands.

Economic consequences were calculated as:

1. Impacts
   - Value of lost output
   - Lost jobs
   - Lost labor income
   - Lost value added
2. Costs
   - In-Delta
   - Statewide
   - Total

The analysis shows the maximum per-island costs of levee failure ranging from minimal to over \$9 billion, with total vulnerability of about \$24 billion, all in terms of 2005 dollars.

DRMS Future Risks

Future risks were considered in terms of the 2005 hazards as they might change with time and also as the Delta environment–climate, sea level, landscape, levee condition, population, infrastructure, and economics–may change over the next 200 years.

The fundamental conclusion of the DRMS future risks analysis was that all significant risk factors will increase with time, some modestly (e.g., tidal amplitude) and others dramatically (e.g., population).

Sacramento–San Joaquin Delta Levee Composite Risk Assessment

To achieve the objective of this work, presenting available Sacramento–San Joaquin Delta levee risk information in a matrix form consistent with USACE and Army policies and suitable for identifying areas of USACE concern, pertinent data were extracted from the DRMS Phase 1 report (URS/JBA 2008):

J. Water Resour. Plann. Manage., 2014, 140(5): 734-743

1. Predicted levee breach probability, expressed as *Annual mean number of failures*.
2. Predicted damage cost estimates for flooding by a 100-year river flood, expressed for each island as the sum of:
   - *Repair costs*
   - *Differential repair costs for point assets* (scour)
   - *Differential repair costs for linear assets* (scour)
   - Predicted maximum potential facilities caused by levee breaching, expressed as *Breach mean (life loss)*.

All the estimates extracted from the DRMS report were for calendar year 2005. Note that this analysis used economic costs to the DRMS' estimate for individual islands and did not include state-wide costs, nor did they include multiple failures such as might occur in a catastrophic event, both of which were reported in the DRMS reports and not repeated here.

CRM Approach

Histograms of the DRMS data were constructed to determine logical intervals for the Hazard and Consequences matrices described in Army Field Manual 5-19 and Engineer Circular EC 1110-2-6062 (USACE 2011b). Economic damages and human fatalities were examined separately, but both analyses employed the same levee breach probability intervals. Finally, each island or other analysis zone (both referred to as *zones* hereafter) was assigned a category from 1 (low) to 5 (high) for both the hazard probability (levee breach) and the consequences (damages and fatalities), producing a matrix of 25 possible combinations. The intervals for each are shown in Tables 2–4.

Two risk indexes—Breach Mean Life Loss and Predicted Damage—were computed for each zone using Eq. (1), the product of the annual mean number of failures and the consequences divided by a normalizing value. The normalizing variable in Eq. (1) was chosen to be the maximum value of the numerator, so that the risk indexes range from 0 to 1.

Choice of intervals for grouping the failure rates and consequences is somewhat arbitrary and can be changed if needed, using the calculated risk indexes to refine the analysis, creating more or fewer categories, according to the application. Complete calculation details are presented in Dynamic Solutions (2012). Extracts are presented and discussed below.

Table 3. Life Loss Risk Matrix with Number of Zones within Each Risk Category

	Annual mean number of failures (category)				
Maximum mean life loss (category)	0–0.01 (1)	0.01–0.025 (2)	0.025–0.05 (3)	0.05–0.1 (4)	>0.1 (5)
>100 (5)	0	0	2	2	1
50–100 (4)	0	0	2	0	2
10–50 (3)	1	0	4	3	2
1–10 (2)	0	0	8	14	7
0–1 (1)	2	0	4	14	9

Table 4. Cost Damage Risk Matrix with Number of Zones Falling within Each Risk Category

	Annual mean number of failures (category)				
Maximum damage costs $M (category)	0–0.01 (1)	0.01–0.025 (2)	0.025–0.05 (3)	0.05–0.1 (4)	>0.1 (5)
>500 (5)	0	2	2	3	1
100–500 (4)	4	2	1	3	6
50–100 (3)	0	0	2	5	3
10–50 (2)	1	1	13	21	18
0–10 (1)	2	1	7	23	22

Table 5. Sixteen Highest Combined Risk Zones, Listed Alphabetically

Zone	Life loss risk index[a]	Damage cost risk index
Bethel_Island	0.1	0.1
Boggs_Tract	0.2	0.1
Brannan-Andrus Island	0.008	0.07
Jones_Tract-Upper_and_Lower	0	0.05
Lincoln_Village_Tract	0.6	0.2
Middle_Roberts Island	0	0.05
RD 17 (Mossdale)	NA	0.2
Sacramento_Pocket_Area	NA	0.4
Sargent_Barnhart_Tract 2	1	0.6
Sherman_Island	0.2	0.04
Shima_Tract	0.6	0.1
SM 124	NA	1
Smith Tract	0.6	0.08
Smith_Tract	0.8	0.2
Tyler_Island 2	0	0.06
West Sacramento North	NA	0.09

[a]NA indicates zones for which life loss predictions were not found in the DRMS report.

CRM Results

The risk matrix, with five levee failure rate categories and five consequences categories, results in 25 possible pairs, which are aggregated into five risk levels labeled and coded as shown in Table 2. Table 3 shows the life loss matrix with the number of zones that fall within each matrix pair. One zone (discussed later) qualifies for the maximum life risk label, with greater than 0.1 failures per year and over 100 lives at risk. Using the five levels of Table 2, seven zones fall within the highest risk level, and 14 fall within the higher risk level. Fifty are in the high, four are in the lower, and two are in the lowest risk level, totaling 77 unique zones categorized for life loss risk.

Table 4 shows the damage cost risk matrix, with five levee failure rate categories and five damage cost categories, resulting in 25 possible pairs which are aggregated into five risk levels labeled and coded as shown in Table 2. Also shown in the table are the number of zones that fall within the damage cost risk matrix. Fourteen zones fall within the highest risk level, and 36 fall within the higher risk level. Eighty-one are in the high, 10 are in the lower, and two are in the lowest risk level, totaling 143 unique zones categorized for damage cost risk. Risk levels for specific zones are discussed below.

Table 5 compares the risk indexes for the zones with the greatest combined risk categories. It also demonstrates that life loss and damage cost predictions were not available for all zones, including some of those with substantial threats.

Figs. 4 and 5 show a Delta Map with the analysis zones coded according to the risk categorization in Table 2. Areas with insufficient data to calculate a risk index are shown as cross-hatched. Complete results can be found in Dynamic Solutions (2012).

Discussion

As was pointed out in the DRMS report, significant uncertainties are inherent in these analyses, and the Department of the Army approach does not reduce those uncertainties. However, the results can be extremely useful when used in a comparative sense and with

J. Water Resour. Plann. Manage., 2014, 140(5): 734-743

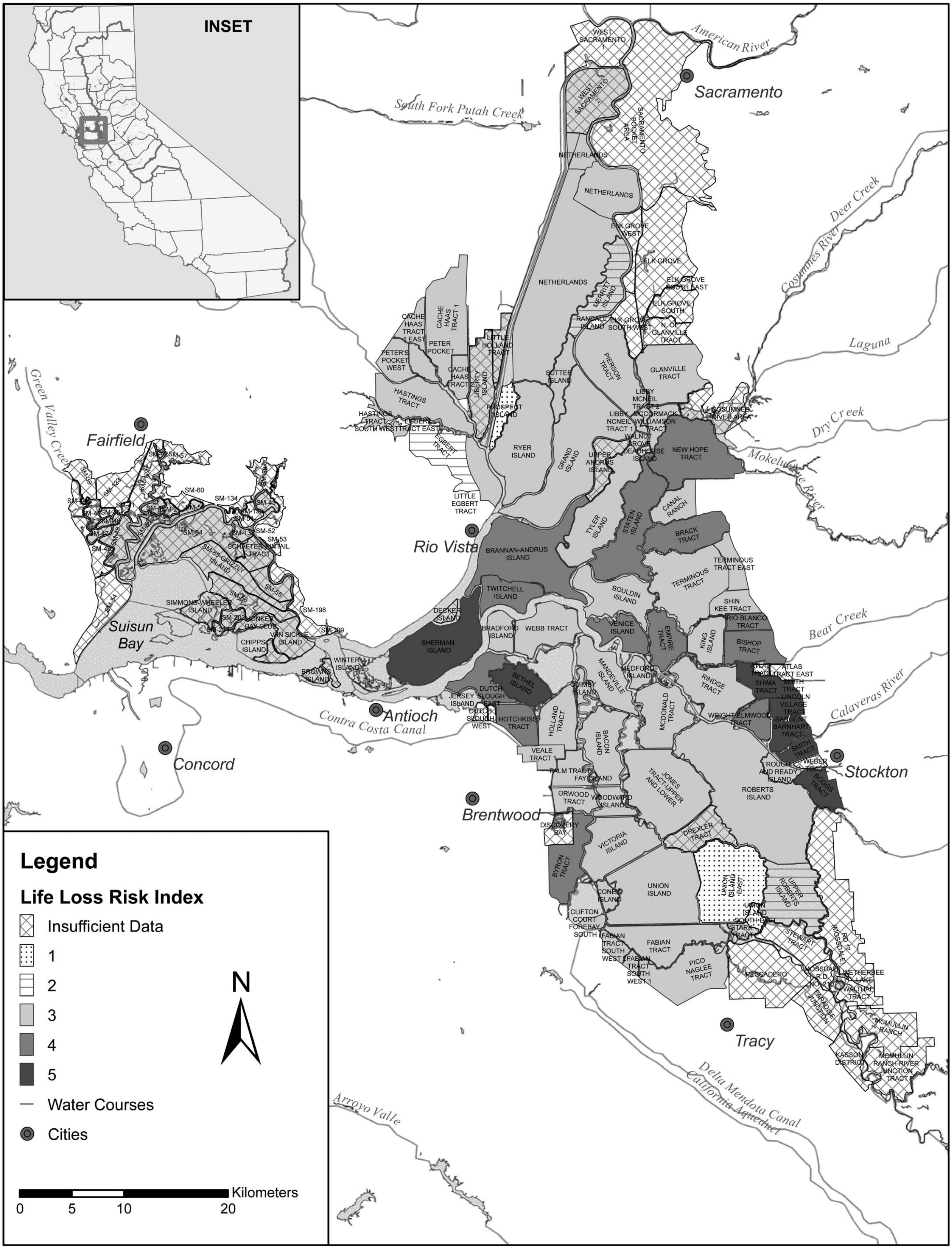

Fig. 4. Life loss indexes in the Delta (reprinted from Dynamic Solutions 2012, with permission)

J. Water Resour. Plann. Manage., 2014, 140(5): 734-743

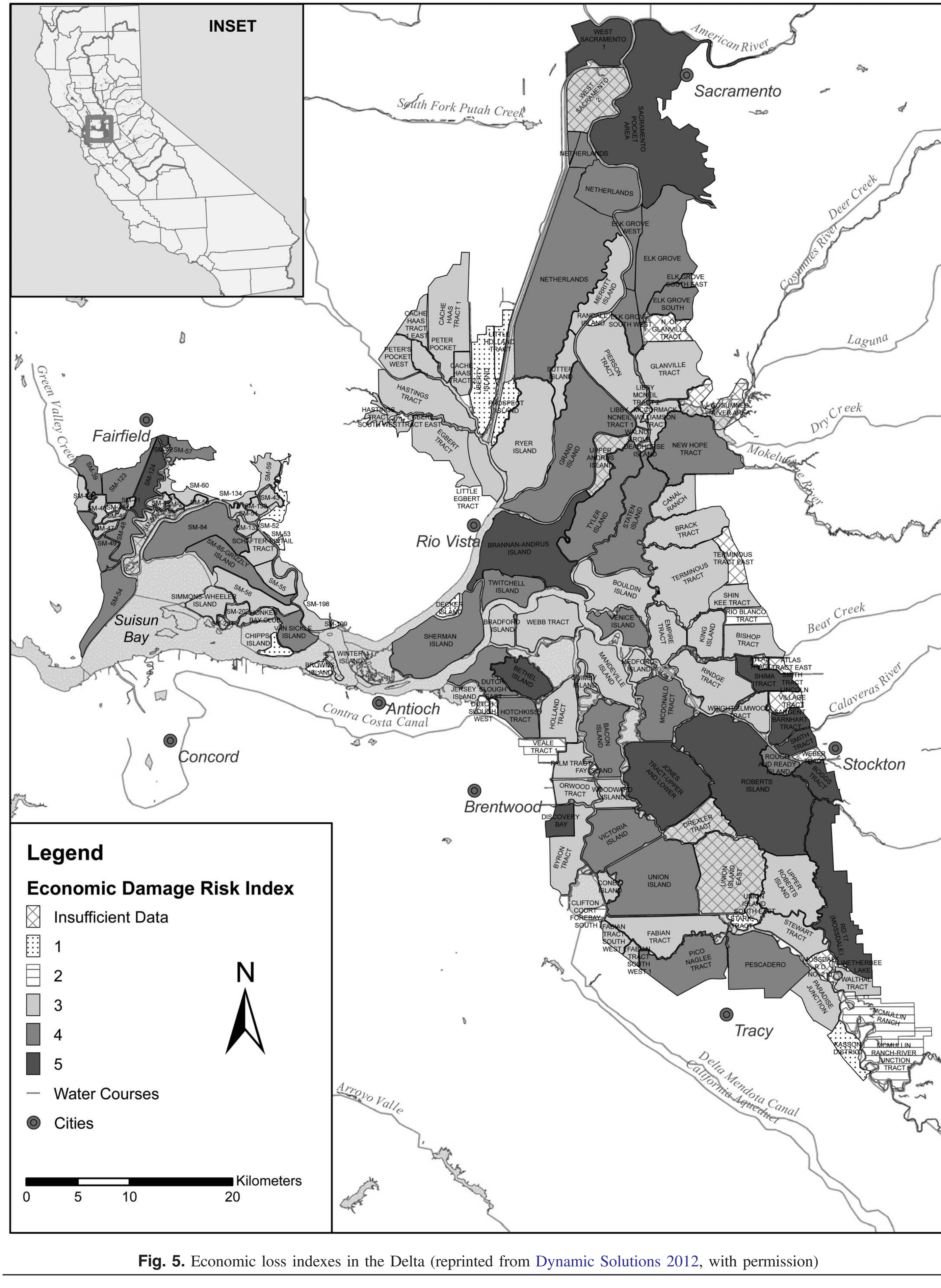

Fig. 5. Economic loss indexes in the Delta (reprinted from Dynamic Solutions 2012, with permission)

Table 6. Listing of Zones Identified as Having Significant Risk by at Least Two Measures

Zone	This paper: Life loss index top 25	This paper: Damage cost index top 25	URS/JBA 2008: Significant island
Bethel Island	X	X	X
Bishop_Tract	X	—	X
Boggs_Tract	X	X	X
Brack Tract	X	—	X
Bradford Island	X	—	X
Brannan-Andrus Island	X	X	X
Byron Tract 1 (127)	X	—	X
Discovery Bay	—	X	X
Empire Tract	X	—	X
Grand Island	—	X	X
Holland Tract	X	—	X
Jersey Island	X	—	X
Jones Tract (Upper and Lower)	—	X	X
Lincoln_Village_Tract	X	X	—
New Hope Tract	X	—	X
Orwood Tract (20)	X	—	X
RD 17 (Mossdale)	—	X	X
Rio Blanco Tract	X	—	X
Roberts Island	—	X	X
Sargent_Barnhart Tract 2	X	X	X
Sherman Island	X	X	X
Shima Tract	X	X	X
Shin Kee Tract	X	—	X
SM-124 (Suisun Marsh, Southwest of Suisun City)	—	X	X
Smith_Tract	X	X	X
Staten Island	X	—	X
Terminous Tract 2 (87)	X	—	X
Twitchell Island	X	—	X
Tyler Island 2 (63)	—	X	X
Venice Island	X	—	X
Webb Tract	X	—	X
West Sacramento North	—	X	X
Wright-Elmwood	X	—	X

careful application of sound judgment. For example, decisions about the priority of levee improvements between Bethel Island and Boggs Tract using Table 5 alone are inadvisable: the differences between their life loss and damage cost indexes are small and statistically insignificant, respectively. However, Sargent Barnhart Tract 2 is shown by Table 5 to be clearly at greater risk (indexes of 1 and 0.6) than either Bethel or Boggs. In the absence of other information, Sargent Barnhart Tract would clearly be a levee repair and rehabilitation priority over most other zones shown.

Table 6 lists the zones that exhibit highest risk indexes in at least two of three categories—the DRMS report Significant Island list and the zones found to at greatest composite risk by the analysis reported here. Zones that appear in all three lists are highlighted with dark shading.

These results show that translating the risks of Delta flooding into a form compatible with Department of the Army and USACE requirements does not change the overall conclusions to be drawn from the DRMS effort and report. However, this translation makes the results compliant with USACE regulations and produces a different prioritized list for management action.

Events of recent years–Hurricane Katrina, Deepwater Horizon explosion, and Tohoku earthquake-tsunami–illustrate the horrific effects of low-probability, high consequence events for which society was ill prepared. The analysis presented here is deliberately biased towards high consequence events–large potential life loss and damage costs–to keep them in focus for the CALFED effort described above.

Although uncertainties in the absolute magnitude of the results make them most useful for comparisons, the actual values of the probabilities and consequences are alarming. For example, Sargent Barnhart Tract, northwest of Stockton, has a mean annual failure rate of 0.07, or an expected levee failure every 14 years, with a probable 96 fatalities for a nighttime seismic-induced failure. Adjacent tracts with only slightly lower failure probabilities put another 500 lives at risk. Zone SM-124 has a projected failure rate of 0.5, or once every two years, with maximum potential damages exceeding $250 million. The Sacramento Pocket Area, with a mean annual failure rate of 0.006, has over $9 billion at risk. Note that *sunny day* failures for SM-124 would not produce the tabulated level of loss, which corresponds to the value of all property at risk that might occur under flood conditions.

Additional analyses are possible–quantification of ecosystem risks and evaluation of human threats among them; however, the evidence for catastrophic life loss and economic damages is more than sufficient to justify risk management through targeted system improvements.

Risk definitions vary widely throughout the literature and practice (Dynamic Solutions 2012), sowing confusion that can be reduced by a consistent set of definitions such as those used by the USACE and others (e.g., Seed et al. 2006; NRC 2009) At least as important as standard risk definitions and reduction in levels of uncertainty are to the Delta is a public that is well informed on the meaning of risk and its implications for policy and funding of public works. Hacker (2012) addressed this point in his controversial New York Times opinion piece suggesting that algebra courses be replaced with a course in *citizen statistics* for many students.

Conclusions

The objectives of this work have been achieved by:

1. Presenting available Sacramento–San Joaquin Delta levee risk information in a matrix form consistent with USACE and Army policies and suitable for identifying areas of USACE concern.
2. Producing example use of the risk information to: (a) assess the probability of an adverse event, (b) estimate the consequences of that event, and (c) define the risk level for that event from the risk matrix.
3. Providing recommendations for improvement of the levee risk assessment and its application.

USACE guidance documents define risk as "probability and severity of loss linked to hazards" and prescribe a composite risk assessment method to be used in USACE projects. The Delta Risk Management Strategy Phase 1 and 2 reports are sound and rigorous analyses of the relative probability of hazards and severity of risks in the Delta and provide the information needed for a risk analysis compliant with USACE requirements.

Tables 5 and 6 provide rank-ordered lists of the highest risk zones – those with the greatest probability of failure combined with the most severe consequences. The originals of those tables (Dynamic Solutions 2012) can be used in a USACE framework to identify needed risk management efforts.

Whereas refinements to these risk estimates are possible, this paper and the Delta Risk Management Strategy analyses provide more than sufficient evidence that flooding in the Sacramento–San Joaquin Delta presents significant risks to California and

J. Water Resour. Plann. Manage., 2014, 140(5): 734-743

the nation. Hundreds of lives and billions of dollar damages are at high probability of occurrence. Urgent action is necessary to manage those risks.

Acknowledgments

The work on which the paper is based was prepared for the USACE, Sacramento District, by Dynamic Solutions, LLC. The authors express their appreciation to Dr. Said Salah-Mars of URS and Dr. Sean Bagheban of California Department of Water Resources for their expert advice and assistance.

References

Aboelata, M., Bowles, D. S., and McClelland, D. M. (2003). "A model for estimating dam failure life loss." *Proc., the Australian Committee on Large Dams Risk Workshop*, Australian National Committee on Large Dams, Hobart, Tasmania, Australia.

CALFED Science Program Independent Review Panel. (2008). "Review of the Delta risk management strategy phase 1 report (draft 4)." ⟨http://www.water.ca.gov/floodmgmt/dsmo/sab/drmsp/docs/IRP_DRMS_Review-main_plus_appendices.pdf⟩ (Nov. 15, 2011).

Dynamic Solutions. (2012). "CALFED/Delta islands & levees feasibility study hydrodynamic models of the Sacramento–San Joaquin Delta." Composite Risk Assessment for Sacramento-San Joaquin Delta Levee System, Knoxville, TN.

Environmental Protection Agency (EPA). (2011). "Frequently asked questions on mortality risk valuation." ⟨http://yosemite.epa.gov/ee/epa/eed.nsf/pages/MortalityRiskValuation.html#whatisvsl⟩ (Sep. 21, 2011).

Hacker, Andrew. (2012). "Is algebra necessary?" New York Times, ⟨http://www.nytimes.com/2012/07/29/opinion/sunday/is-algebra-necessary.html?pagewanted=all&r=0⟩ (Nov. 28, 2012).

ISO. (2009). *Risk management—Principles and guidelines*, ISO 31000:2009, Int. Organization for Standardization, Geneva.

National Research Council (NRC), Committee on Improving Risk Analysis Approaches Used by the U.S. EPA, Board on Environmental Studies, and Toxicology, Division on Earth, and Life Studies. (2009). *Science and decisions: Advancing risk assessment*, The National Academies Press, Washington, DC.

NRC. (2007). *Scientific review of the proposed risk assessment bulletin from the office of management and budget*, National Academies Press, ⟨http://www.nap.edu/catalog/11811.html⟩ (Nov. 3, 2011).

Seed, R. B., et al. (2006). "Investigation of the performance of the New Orleans flood protection systems in Hurricane Katrina on August 29, 2005." ⟨http://www.ce.berkeley.edu/projects/neworleans/⟩ (Nov. 10, 2012).

URS/JBA. (2008). "Delta risk management strategy (DRMS), phase 1, draft 4." *Risk Analysis Rep.*, URS Corporation.

URS/JBA. (2011). "Delta risk management strategy (DRMS)." *Phase 2 Rep.*, URS Corporation.

U.S. Army. (2006). *Composite risk management, field manual No. 5-19 (100-14)*, Headquarters Dept. of the Army, Washington, DC.

U.S. Army Corps of Engineers (USACE). (1996). "Risk-based analysis for flood damage reduction studies." *Rep. EM 1110-2-1619*, Washington, DC.

USACE. (2002). "Sacramento and San Joaquin River basins, California, comprehensive study." *Interim Rep.*, Reclamation Board of State of California and USACE, Sacramento District, CA.

USACE. (2010). "Process for the national flood insurance program (NFIP) levee system evaluation." *Rep. EC 1110-2-6067*, Washington, DC.

USACE. (2011a). "Introduction to risk analysis, risk analysis gateway." ⟨http://corpsriskanalysisgateway.us/lms/ch2-Risks.cfm⟩ (Aug. 15, 2011).

USACE. (2011b). "Risk and reliability engineering for major rehabilitation studies." *Rep. EC 1110-2-6062*, Washington, DC.

J. Water Resour. Plann. Manage., 2014, 140(5): 734-743