Analyzing Flood Protection Measures of Levee Systems in Arkansas

Han-suk Sohn
Dept. of Industrial Engineering,
New Mexico State University
Las Cruces, NM 88003, USA
hsohn@nmsu.edu

Christine J. Sohn
College of Letters and Science,
University of California-Los Angeles
Los Angeles, CA 90095, USA
cjsohn@ucla.edu

***Abstract*— This paper presents an optimization model and its application for analyzing flood protection measures of levee systems. The applicability of the proposed model is demonstrated in the case study of Arkansas' levee systems. The results demonstrate that the proposed model is a practical and flexible tool for the identification of optimal spending by levee that could reduce the risk caused by lack of maintenance. Results in this study show that budget changes and disbursement options affect the choice and proportion of repairs assigned to each levee.**

Keywords—Levee system; flood protection measures; sensitivity analysis; Arkansas

I. Introduction

During the year 2019, the state of Arkansas suffered millions of U.S. dollars in damages due to flooding and levee breaches. After such losses, the governor of the state through the Executive Order 19-10 formed a Task Force to create recommendations for monitoring and maintaining the levees in the state [1]. The governor also requested legislative approval for spending ten million dollars through the Arkansas Department of Emergency Services (ADEM) for immediate repairs to the levee system. According to the American Society of Civil Engineers (2014), who rates the infrastructures of various U.S. states, the score for the Arkansas levees is a "D" [2]. As their report analyzes only thirteen levee systems, this small sample may not accurately reflect all the different levees in the state. However, the resulted score for the levees in Arkansas still indicates how bad the current conditions of the levees are, which may eventually put thousands of homes in danger.

Although the levee systems have gained much attention over the past decade, much of the research efforts have been focused on maintaining or repairing other structures. Studies in the state associated with levees often focus on rice production and water use [3], while studies on structure integrity [4]-[5] focus on the geophysical aspects of the levee, and are often limited to a small geographical area. A large portion of studies related to replacement and repair are also based on the manufacturing industry [6]-[7]. One of the most promising methodological approaches used in this research domain is mathematical modeling. Studies in [6] used a mixed integer linear program (MILP) to schedule preventive maintenance while attempting to minimize the total costs. Their proposed model went beyond the basic replacement schedule and took into consideration the cost of spare parts and of any further repairs made necessary by unpredicted failure. Gosavi [8] used Markov decision process model to develop a risk-sensitive preventive maintenance plan. Other popular mathematical modeling techniques used in this domain include nonlinear mixed-integer program model [9], a decision support model based on greedy algorithms [10]-[11], and other non-optimal analytical modeling approaches [12]. Despite all of these fruitful researches, the formal investigation of repairing levees under limited-budget conditions is still insufficient. In this short paper, therefore, we present a simple yet practical optimization approach, which employs a linear program, to investigate how to minimize damage risks in the state of Arkansans under a limited budget.

II. Problem Statement

The state of Arkansas has a restricted budget for repairs and a limited knowledge of the current status of its levee systems. Based on such limitations, this study proposes an optimization model that minimizes current damage risk (measured in dollars) while using current available public information.

A. *Data and Assumptions*

The majority of the data used in this report is based on the National Levee Database [13], which is a project maintained by the US Army Corps of

Engineers with a partnership with the Federal Emergency Management Agency (FEMA). The full database has 10,808 levee segments with 8,901 systems.

While the original dataset contains over 60 different variables, this study only uses a limited amount of such information. Some of the available information is related to spatial characteristics of the levees and other qualitative characteristics that are not pertinent to this report. Some of the other variables available in the original dataset are the length of the levees (in miles), levee overtopping Annual Chance of Exceedance (ACE), levee segment and system unique identifiers, last periodic inspection, last routine inspection, estimated property value, and Levee Safety Action Classification (LSAC) rating.

The high level of non-standardization in the categorical variables were one of the main issues why such variables were not incorporated into this report. For example, the LSAC rating is separated into five different groups (i.e., urgent & compelling, urgent, high priority, priority, and normal). As explained by [14], the primary factors of those ratings are elevation, hydraulic history, performance, and consequences (i.e. economic life). Since the currently available dataset does not provide the full level of details connected to the final rating, the use of such information would not contribute to the study as levees with similar performance issues but different population-at-risk (PAR) levels may have equivalent ratings.

In the state of Arkansas, there are 164 levee segments and 114 systems. Fig. 1 shows all of the levees in the state and indicates whether each one is maintained by U.S. Army Corps of Engineer (USACE) or not. Additionally, it includes the area that is protected by the levees.

Fig. 1. ARKANSAS LEVEES USACE STATUS AND LEVEED AREA (SOURCE: [13])

B. Levee Repair Costs

The data regarding levee repairs are connected to the height of the levees and their characteristics. One of the reports that provide detailed cost information for levee repairs is the FEMA Floodproofing for Non-Residential Structures [15]. According to the report, the cost of constructing a levee can range between $13 per foot for a 3 foot levee to $85 per foot for a 10 foot levee (not zoned). Since the report is based on 1986 U.S. dollars, the values were adjusted by inflation to reflect expected 2020 U.S. dollars. Using data from the Bureau of Labor Statistics Consumer Price Index (CPI) inflation calculator, the cost of repair for January 2019 was estimated [16]. Note that we assumed a 2.3% inflation as the change from 2019 to 2020. These calculations resulted in the new construction cost per foot for a 3 foot levee to be $30.55. It is important to note that the CPI is based on the average basket of consumer goods, and as such, construction costs during 1986 to 2020 may have changed by a different amount than the CPI suggests. Even with those limitations, CPI is a measure widely used to estimate inflation, and as such it is expected to measure with some level of veridicality the construction cost changes since 1986. The FEMA report also presents estimates for annual damages to the structure, similar to the construction cost. Those estimates are based on the height of levee and flood levels and, in this study, the value for the expected annual damage is set as 0.5%.

C. Data Cleaning and Analysis

Since USACE repairs and monitors their own levees, the levees which were maintained by USACE are not part of the levees of interest. This is based on the assumption that the government funds would go towards levees that do not have a steady funding source. This decision led to over 3,313 observations being dropped from the original dataset, leaving a new total of only 7,497 observations.

There were also some missing values related to estimated property damage, overtopping ACE, and year of construction. Missing values for estimated property damage due to flooding, year of construction and overtopping ACE were generated using pseudo-random generator. The pseudo-random number generator was restricted to between the highest and lowest observed values for the US dataset. There were levees that were yet to be constructed (i.e. construction year 2021), as such the highest used in the generator was modified to include the second highest value. Since the online database (National Levee Database) did not provide the detailed ACE information in the download files, inputting each value had to be done manually.

As this study is based on a single state only, the final dataset for the group of interest has 55 levees, all identified as locally constructed, operated, maintained and located in the state of Arkansas. Note that data changes were made using the Python Programming Language.

III. NOTATION

The notation used throughout this paper is stated below:

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i levee system (reassigned levee system id)

Data

l_i length of levee (in miles)
d_i estimated property damage (in USD)
D_i total estimated property damage
o_i cost of levee repair due to height
C_i total cost of repair levee
v_i year levee i was constructed
t year of repair (i.e. 2020)
g scalar for expected annual damage to structure
b scalar for the state repair budget

Decision Variables

r_i level of repair on the levee

IV. PROBLEM FORMULATION

The repair cost for each levee is set as:

$$C_i = 5280 \cdot l_i \cdot o_i \quad (1)$$

where (l_i/5280) is the conversion of levee length (in miles) to feet, and o_i is the cost of repair based on height. As shown in Floodproofing Non-Residential Structures [15], levee heights are related to overtopping ACE under the assumption that such relationship would be maintained in the failure rate. This may not be a strong assumption as the material used in the construction of levees with the same height may differ. However, due to the currently available information, this assumption had to be made. The cost of levee repair due to height is estimated as follows:

$$o_i = \frac{1.5275}{overtopping\ ACE_i} \quad (2)$$

In the case of repairing a levee with an overtopping ACE value of 0.05 (the highest value in the data), the cost would be $30.55 per foot. As previously stated, $30.55 would be the inflation adjusted cost presented by the FEMA estimates [15]. The total estimated risk to a property related to each levee is set as:

$$D_i = (t - v_i) \cdot g \cdot d_i \quad (3)$$

where ($t - v_i$) is the age of levee i; g is the estimated annual damage to the structures (i.e., 0.005); and d_i is the estimated property damage (in USD). The objective function of the model is set as:

$$\text{Minimize } \sum_i D_i - \sum_i D_i(r_i) \quad (4)$$

Subject to the following constraints:

1. The first constraint is based on the limited monetary funds for fixing the levees. In this study, the value of b is set as $10 million.

$$\sum_i C_i(r_i) \le b$$

2. The second constraint is the restrictions on the value of r_i. The values for r_i could be understood as the percentage repair to the levee i, where the value of 1 indicates 100% of repair of damages.

$$0 \le r_i \le 1$$

V. RESULTS AND DISCUSSION

The proposed model was solved using the CPLEX solver as a Linear Programming problem using the General Algebraic Modeling System (GAMS) software. Before proceeding to the results, some special conditions under which this study was conducted should be noted. This study has a variety of limitations that may decrease its accuracy and applicability, and they are summarized as follows:

- The availability and quality of the data used in the model. Since some of the information in the tables (e.g. damage values) were inputted manually, errors could exist, further limiting the model accuracy
- Beyond the issue of data quality, the lack of information such as hydrological, temporal and geographical features can reduce the scope and applicability of the model
- The proposed model assumes that repairs and the change in the reduction of risk have a linear relationship, which may not be true for all levees

As can be seen in Table 1, 25 levees were fully repaired while 1 levee was partially repaired. The total estimated excess risk under this modelling is $46,588,207.92. This means that after such repairs there are areas that contain an additional risk of failure, that when combined, could lead to around $46 million of damages. It is important to remember that this is not the total area that could be damaged by levee failure; rather, it is the area with a risk level above a non-damaged structure.

VI. SENSITIVITY ANALYSIS

The sensitivity analysis for this paper is based on the modification of two initial parameters. The first is a relaxation of the budget constraint accounting for additional funds. The second is a change of the year of construction and its contribution to the delayed release of funds.

A. *Relaxed Budget Constraint*

In this section, the budget constraint which was originally set as $10 million was modified. As stated in the introduction, this budget was based on the statement by the Arkansas' governor. However, the governor has a group investigating the current situation of the levees in the state. This group will present their findings on December 31, 2019. This section uses an incremental change to the budget ($1 million) to further understand how such change would impact levee repairs. The changes to the budget occur up to $20 million and the findings are presented in Fig 2. The figure focuses on full levee repair, and as incremental changes in the budget increase the number of complete repairs increases to up to 33 full repairs; after such point and up to the end of the new budget (i.e. $20 million) there are no new full levee repairs and the repairs are only partial.

B. Change in Disbursement Year

Since the model budget assumptions are based on the funds that would be available by 2020, it is worthwhile to try to understand whether changing the budget release time will impact the levees being repaired or not. Since the cost of repair and current estimated damage are based on the levee's age, by releasing the funds later, the levee risk would be higher as the difference between ($t - v_i$) would be changed. The results are presented in Table 2. By changing the year to 2021, the optimal value has increased by approximately $1.2 million, leading to a new optimal value of $47,820,541.45. While the magnitude is surprising, this change in optimal value was expected as delaying the release of money incurred an additional year of damages to the structures.

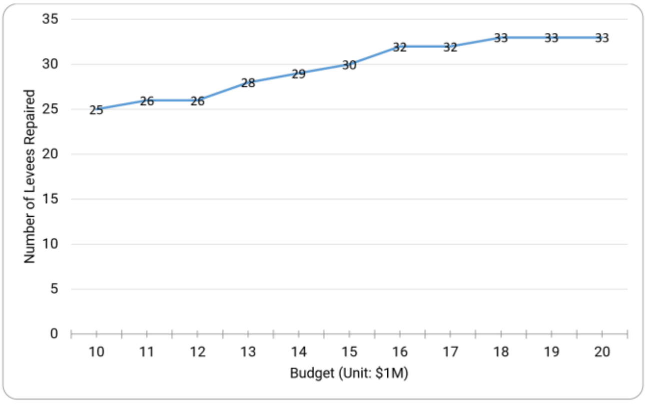

Fig. 2. NUMBER OF LEVEES REPAIRED BY BUDGET AVAILABILITY

VII. CONCLUSION AND FUTURE RESEARCH

This study presented a way to use a rather common mathematical programming technique to gain insight into analyzing flood protection measures of levee systems. Although the availability of data was limited, through the case study of Arkansas, we have found that the proposed optimization model guides us in making the right decision on how to assign repair ratios to damaged structures and how to minimize the excess damage risks under the limited budget situation. The sensitivity analysis also helps us to understand how changing the year of construction influences the timing of the release of funds.

Future research should focus on adding updated information, which will be released by the state at the end of the year. The improved data availability and quality of information has the potential to greatly increase the applicability of the proposed model.

REFERENCES

[1] State of Arkansas Executive Department. Executive Order to Establish the Arkansas Levee Task Force. 2019

[2] American Society of Civil Engineers. 2014 Report Card for Arkansas' Infrastructure. 2014

[3] C.G. Henry, S.L. Hirsh, M.M. Anders, E.D. Vories, M.L. Reba, K.B. Watkins, and J.T. Hardke. "Annual irrigation water use for Arkansas rice production." Journal of Irrigation and Drainage Engineering 142, no. 11 (2016): 05016006.

[4] H.K. Chlaib, H. Mahdi, H. Al-Shukri, M.M. Su, A. Catakli, and N. Abd. "Using ground penetrating radar in levee assessment to detect small scale animal burrows." *Journal of Applied Geophysics* 103 (2014): 121-131.

[5] J.A. Gillip and J.D. Payne, Geophysical Characterization of the Lollie Levee near Conway, Arkansas, using Capacitively Coupled Resistivity, Coring and Direct Push Logging. 2011.

[6] R. Manzini, R. Accorsi, T. Cennerazzo, E. Ferrari, and F. Maranesi. "The scheduling of maintenance. A resource-constraints mixed integer linear programming model." Computers & Industrial Engineering 87 (2015): 561-568.

[7] A. Grigoriev, J.V. de Klundert, and F. Spieksma. "Modeling and solving the periodic maintenance problem." *European journal of operational research* 172, no. 3 (2006): 783-797.

[8] A. Gosavi, "A risk-sensitive approach to total productive maintenance." *Automatica* 42, no. 8 (2006): 1321-1330.

[9] K.S. Moghaddam and J.S. Usher. "Preventive maintenance and replacement scheduling for repairable and maintainable systems using dynamic programming." *Computers & Industrial Engineering* 60, no. 4 (2011): 654-665.

[10] S. Anily, C.A. Glass, and R. Hassin. "The scheduling of maintenance service." *Discrete Applied Mathematics* 82, no. 1-3 (1998): 27-42.

[11] G. Budai, D. Huisman, and R. Dekker. "Scheduling preventive railway maintenance activities." *Journal of the Operational Research Society* 57, no. 9 (2006): 1035-1044.

[12] S. Anily, C.A. Glass and R. Hassin. "Scheduling maintenance services to three machines." *Annals of Operations Research* 86 (1999): 375-391.

[13] U.S. Army Corps of Engineers. National Levee Database. https://levees.sec.usace.army.mil/#/. 2016. (Accessed October 2,2019)

[14] R. Varuso, USACE Levee Screening Tool: Understanding the Classificatio

[15] U.S. Federal Emergency Management Agency. Floodproofing Non-Residential Structures (Chapter 5). May 1986. *https://www.fema.gov/media-*

library/assets/documents/15599 (Accessed October 2, 2019)

[16] Bureau of Labor Statistics. CPI Inflation Calculator. https://data.bls.gov/cgi-bin/cpicalc.pl n.d.(Accessed November 10, 2019)

Table 1. Repair Percentage by Levee

ID #	Segment ID	Description	Repair (%)	ID #	Segment ID	Description	Repair (%)
i1	1604881589	Agricultural Levee	100	i29	1604881735	Ogden Levee 7	0
i2	3704000053	Bateman Levee District No. 3	100	i30	1604881729	Ogden Levee 1	0
i3	1604881592	Cache River Levee 1	0	i31	3704000066	Ormand Peters Private Levee	0
i4	1604881593	Cache River Levee 2	0	i32	1604881588	Overflow Creek Levee	100
i5	1604881755	Crooked Creek Levee 1	100	i33	3704000054	Padgett Island Levee District	0
i6	1604881756	Crooked Creek Levee 2	100	i34	3704000056	Perry County Levee District No. 1	0
i7	3704000052	Curia Creek Drainage District	0	i35	1604991526	Prairie Levee West 2	0
i8	1604771318	East of Hemstead Levee 1	29.12	i36	1604991527	Prairie Levee - Central North	0
i9	1604771320	East of Hemstead Levee 2	100	i37	1604995016	Prairie Levee West 1	0
i10	1604115007	East Point Remove Levee	100	i38	3704000069	Pulaski County Farm Private Levee	100
i11	1604123002	Tupelo Bayou Levee	0	i39	1604115004	West Portland Bottoms Levee	100
i12	1604991497	Agricultural Levee - Lincoln County	0	i40	1604115005	East Portland Bottoms Levee	0
i13	3704000059	Holla Bend Drainage and Levee District No. 2	100	i41	3704000067	Sloan Private Levee	100
i14	3704000057	Holly Bend Levee District No. 1	0	i42	1604109005	South Grand Lake Levee	0
i15	1604881728	Hurricane Creek Lake Levee	100	i43	3704000068	Stalling Private Levee	100
i16	1604885727	Johnson Ditch Levee	100	i44	1604170001	Strong Sewage Treatment Plane Levee	0
i17	3704000062	Little Private Levee	0	i45	3704000049	T.A. Gibson Private Levee	100
i18	1604881584	Little Red River Canal A Levee 2	0	i46	1604135007	Boyd Point Cutoff	0
i19	1604881585	Little Red River Canal A Levee 1	0	i47	1604881739	Walnut Bayou Levee 3	100
i20	1604995009	Little Red River Canal B Levee 2	100	i48	1604881737	Walnut Bayou Levee 1	0
i21	1604881587	Little Red River Canal B Levee 3	0	i49	1604881738	Walnut Bayou Levee 2	100
i22	1604881586	Little Red River Canal B Levee 1	100	i50	1604881757	West Fork White River Agricultural Levee	100
i23	1604771319	Lower Red Lake Ring Levee (Hempstead)	0	i51	1604991531	Woodruff Levee West	100
i24	1604881591	Merrisach Lake Levee	0	i52	1604995000	Woodruff Levee West 2	100
i25	1604109004	North Grand Lake Levee	0	i53	1604995001	Woodruff Levee West 3	100
i26	1604771321	North of Hemstead Levee	0	i54	1604995002	Woodruff Levee West 4	100
i27	1604881734	Ogden Levee 6	100	i55	1604995003	Woodruff Levee West 5	0
i28	1604881736	Ogden Levee 8	0				

Table 2. Results from Changing in Disbursement Year

ID #	Segment ID	Repair (%)		Difference	ID #	Segment ID	Repair (%)		Difference
		Disbursement 2020	Disbursement 2021				Disbursement 2020	Disbursement 2021	
i1	1604881589	100.00	100.00	0.00	i29	1604881735	0.00	0.00	0.00
i2	3704000053	100.00	100.00	0.00	i30	1604881729	0.00	0.00	0.00
i3	1604881592	0.00	0.00	0.00	i31	3704000066	0.00	0.00	0.00
i4	1604881593	0.00	0.00	0.00	i32	1604881588	100.00	100.00	0.00
i5	1604881755	100.00	100.00	0.00	i33	3704000054	0.00	0.00	0.00
i6	1604881756	100.00	100.00	0.00	i34	3704000056	0.00	0.00	0.00
i7	3704000052	0.00	0.00	0.00	i35	1604991526	0.00	0.00	0.00
i8	1604771318	29.12	0.00	-29.12	i36	1604991527	0.00	32.55	32.55
i9	1604771320	100.00	100.00	0.00	i37	1604995016	0.00	0.00	0.00
i10	1604115007	100.00	100.00	0.00	i38	3704000069	100.00	100.00	0.00
i11	1604123002	0.00	0.00	0.00	i39	1604115004	100.00	100.00	0.00
i12	1604991497	0.00	0.00	0.00	i40	1604115005	0.00	0.00	0.00
i13	3704000059	100.00	100.00	0.00	i41	3704000067	100.00	100.00	0.00
i14	3704000057	0.00	0.00	0.00	i42	1604109005	0.00	0.00	0.00
i15	1604881728	100.00	100.00	0.00	i43	3704000068	100.00	100.00	0.00
i16	1604885727	100.00	100.00	0.00	i44	1604170001	0.00	0.00	0.00
i17	3704000062	0.00	0.00	0.00	i45	3704000049	100.00	100.00	0.00
i18	1604881584	0.00	0.00	0.00	i46	1604135007	0.00	0.00	0.00
i19	1604881585	0.00	0.00	0.00	i47	1604881739	100.00	100.00	0.00
i20	1604995009	100.00	100.00	0.00	i48	1604881737	0.00	0.00	0.00
i21	1604881587	0.00	0.00	0.00	i49	1604881738	100.00	100.00	0.00
i22	1604881586	100.00	100.00	0.00	i50	1604881757	100.00	100.00	0.00
i23	1604771319	0.00	0.00	0.00	i51	1604991531	100.00	100.00	0.00
i24	1604881591	0.00	0.00	0.00	i52	1604995000	100.00	100.00	0.00
i25	1604109004	0.00	0.00	0.00	i53	1604995001	100.00	100.00	0.00
i26	1604771321	0.00	0.00	0.00	i54	1604995002	100.00	100.00	0.00
i27	1604881734	100.00	100.00	0.00	i55	1604995003	0.00	0.00	0.00
i28	1604881736	0.00	0.00	0.00					