Utah State University

GIS in Water Resources

CEE 6440

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Underseepage Analysis in levees using GIS

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Introduction

Levees are embankments designed to prevent the flooding of a river into an adjacent landward floodplain as shown in Figure 1. They are exposed to different types of failure modes depending on the behavior of the river and the areas that surround them. One of the most important failure modes is underseepage (flow of water through soils) where an open path called a "pipe" forms under the levee leading it to instability. This failure mode has been a concern around the Sacramento River in California for many years and received more attention after New Orleans' flood event in 2005.

When underseepage flows beneath the levee, two conditions can occur:

1. The water may seep out gently doing no harm to the levee, or
2. Where critical combinations of water levels, soil types and foundation stratigraphy are present, the water can erode the soil, beginning at the seepage exit point and progressing towards the water side of the levee (piping).

Because levees are long structures parallel to rivers, the analyses get to be complex and variable but engineers have been simulating them as simple as possible by means of a deterministic factor of safety.

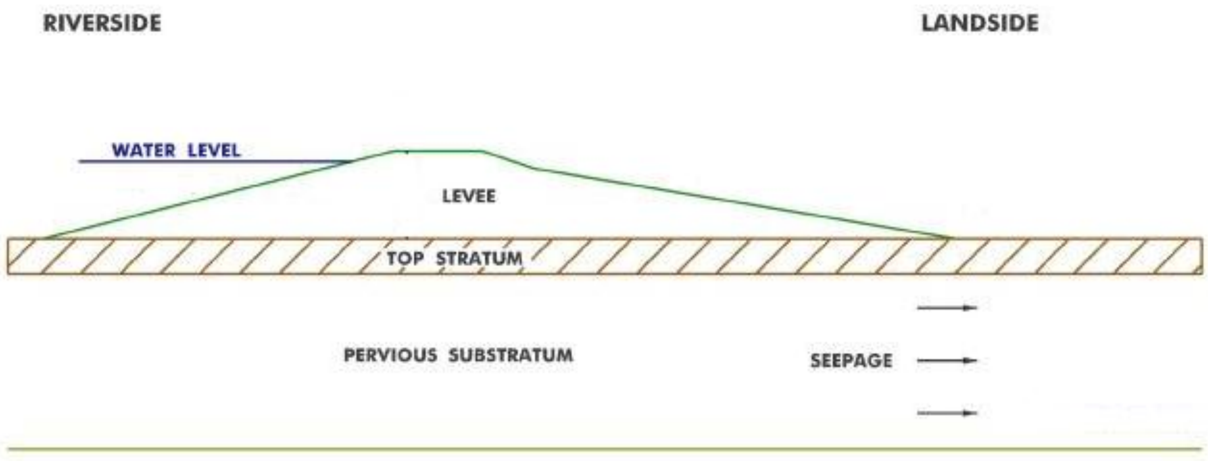


Figure 1. Typical river levee cross-section showing its different parts.
From US Army Corps of Engineers, Memphis District

The intent of this project is to produce and present an informative map showing vulnerable leveed areas along the Natomas Basin near Sacramento, California based on underseepage analysis. Also, it is of interest to show possible flooded depths of the area if the levee system were to fail. It is important to mention that due to the lack of time and information/data this is a pilot analysis. Assumptions were made that might not provide the most accurate results but are good enough for an initial interpretation of vulnerable areas. In addition, this analysis provides a great exercise to work out geotechnical engineering problems with the help of GIS.

Location and importance of research

The Natomas Basin is located near Sacramento, California. As shown in Figure 2, it is surrounded by long levees which include the Natomas Cross Canal, the Natomas East Main Drainage Canal, part of the American River North and Sacramento River North levees. According to the California Department of Conservation (2007), Native Americans settled in the oak woodlands, grasslands and, along the marshland banks of the Sacramento River. Beginning early last century, much of the basin was drained for agriculture and levees were built for flood protection. The cores of today’s levees are often somewhat the levees built by farmers and settlers as much as 150 years ago. Early levees were not constructed to current engineering standards, and little care was given to the suitability of foundation soils. Since the levees were not treated as they should have, there have been multiple failures along the levees like the 1986 flood event (SAFCA, 2008). For the purpose of this project, only the Sacramento River North levees have been analyzed. A closer look of the levees in plan-view is shown on Figure 3.

The importance of this research relies on what can be found in the Natomas Basin. A land use map for the Natomas Basin is presented as Figure 4 and a description of the legend for this map is presented as Table 1. Although there is a lot of cropped area at the north, there is also a lot of development located at the south of the basin placing this population on a risk flooding-area.

Figure 2. Natomas Basin and surrounding levees.

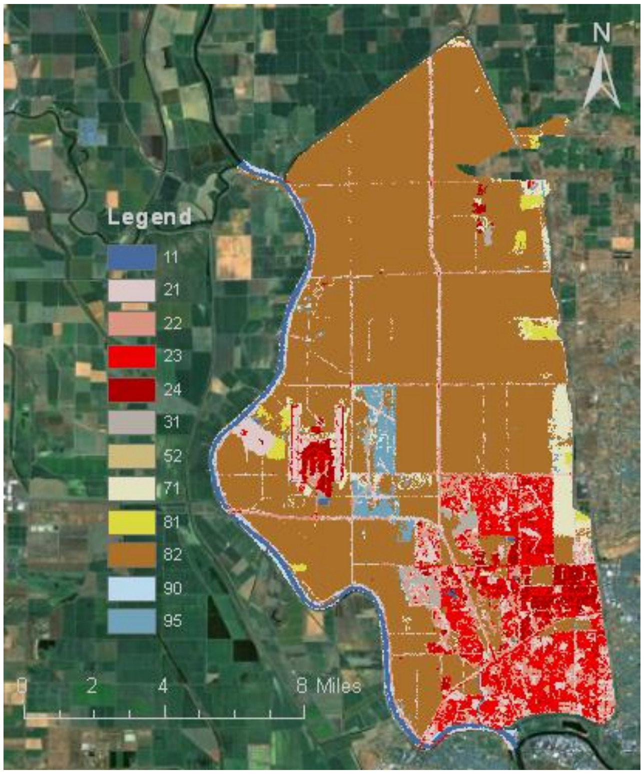


Figure 4. Land use for the Natomas Basin.

Figure 3. Plan-view of Sacramento River North levees.

Table 1. Legend description for Figure 4

VALUE	DESCRIPTION
11	Open Water
21	Developed, Open Space
22	Developed, Low Intensity
23	Developed, Medium Intensity
24	Developed, High Intensity
31	Barren Land (Rock/Sand/Clay)
52	Shrub/Scrub
71	Grassland/Herbaceous
81	Pasture/Hay
82	Cultivated Crops
90	Woody Wetlands
95	Emergent Herbaceous Wetlands

Analysis of Data

The deterministic factor of safety has been used by engineers to calculate the relative stability with respect to underseepage. Based on the initiation of piping is generally defined by the equation (Wolff, 2008):

$$FS = \frac{i_c}{i_e}$$

The critical gradient (i_c) is the gradient needed to initiate erosion. Critical gradient values usually vary from about 0.80 to 1.0 (Mansur et al., 2000), and it is generally taken to be a function of the effective unit weight of the soil (γ') and the unit weight of the water:

$$i_c = \frac{\gamma'}{\gamma_w} = \frac{\gamma_{sat} - \gamma_w}{\gamma_w}$$

The exit gradient (i_e) is the gradient at the point of erosion calculated with Finite Element Analysis or by deterministic formulas like the Blanket Theory equation (USACE, 2000 and USACE, 2005) and it's a function of soil properties, subsurface geometry, and permeability of the subsurface soils.

The calculated FS against underseepage failure is used to provide a theoretical design margin of stability or instability and its value is related to the lack of confidence in the design process and input parameters. It is thought that if the F.S. > 1 the system is stable and might not fail, and if the F.S. < 1 the system is unstable and may fail. Generally, for underseepage a F.S. > 3 is acceptable.

When analyzing underseepage (initiation of erosion) in levees, geotechnical engineers are interest in high flow events like the 100-yr flood event. In order to compute exit gradients for an event of this matter, engineers compute a piezometric head based on the approximated water level for the desired flow event. Since there was no success in either gathering 100-yr flood water levels or piezometric heads, computed hydraulic exit gradients were used instead.

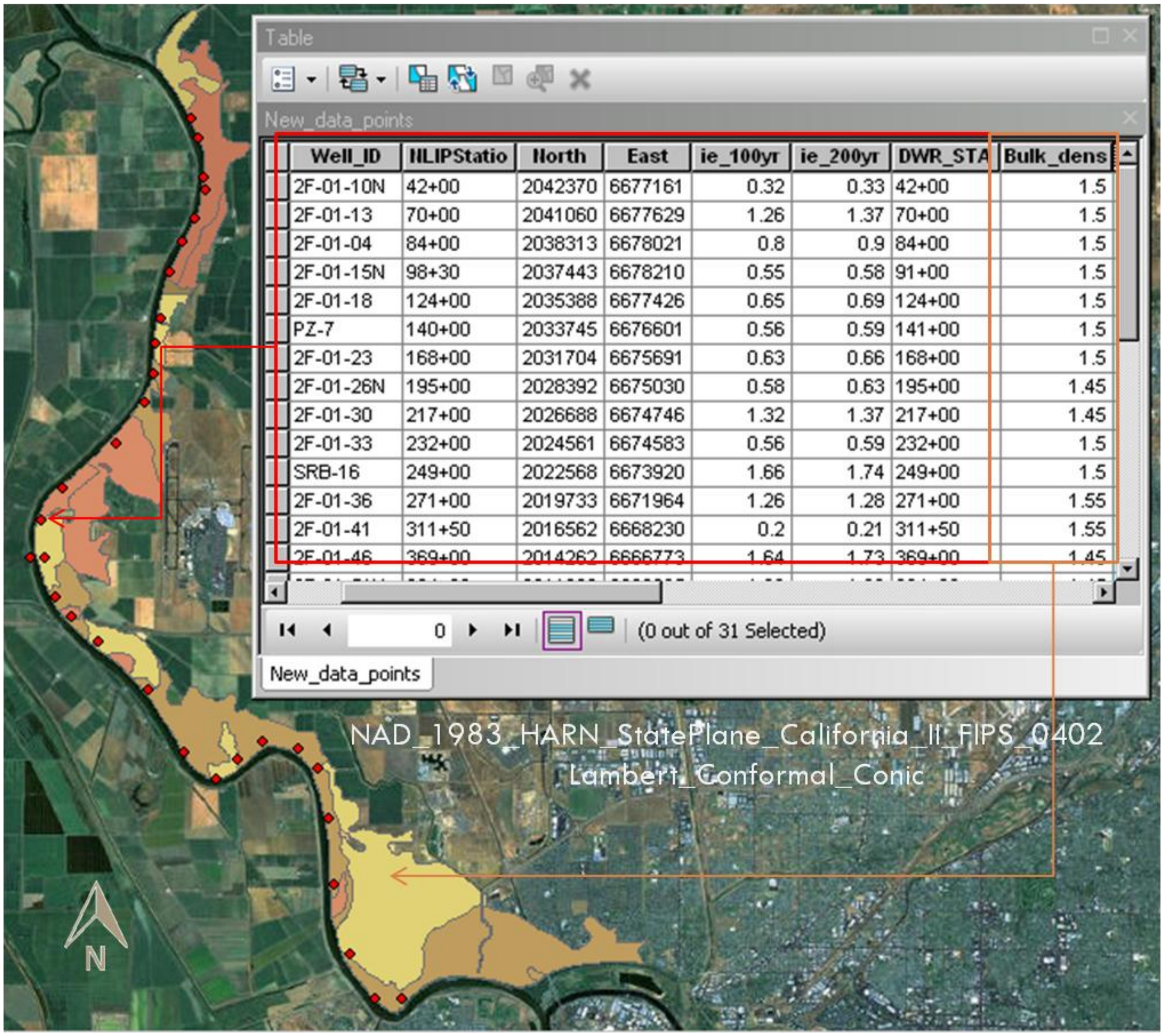
These exit gradients were gathered from a summary report presented to the US Army Corps of Engineers by geotechnical consultant engineers in the Sacramento District area. This report provided coordinates for the analyzed levee sections which made it useful for the purpose of this project. It was specified in the report that the data had the projected California state plane coordinates (northing and easting) NAD_1983_HARN_StatePlane_California_II_FIPS_0402, Lambert_Conformal_Conic. Table 2 presents the data in the Excel-file format used to display the points in ArcGIS.

With respect to the computation of the critical gradient, data was gathered from the Soil Survey Geographic (SSURGO) Database that provided an average moist unit weight (bulk density) of the surface soils. It was assumed that the surface soils continued vertically below the levee and only the soils near the levee system were used. As shown on Figure 5, bulk density values were assigned to each data point (exit gradients) according to their location.

Several steps were needed in order to compute the critical gradients. As mentioned, the critical gradient is a function of the effective unit weight of the soil which implies using the saturated unit weight of the soil. Since SSURGO data provides moist unit weight, the saturated density can be found by simple weight-volume relationships as shown in Holtz and Kovacs (1981) or Das (2007). Assuming the soils are 100 percent saturated, the formula becomes:

Table 2. Gathered exit gradients from the US Army Corps of Engineers summary report

Well ID	NLIPStation	North	East	100yr - i_e	200yr - i_e	DWR STATION
2F-01-10N	42+00	2042370	6677161	0.32	0.33	42+00
2F-01-13	70+00	2041060	6677629	1.26	1.37	70+00
2F-01-04	84+00	2038313	6678021	0.8	0.9	84+00
2F-01-15N	98+30	2037443	6678210	0.55	0.58	91+00
2F-01-18	124+00	2035388	6677426	0.65	0.69	124+00
PZ-7	140+00	2033745	6676601	0.56	0.59	141+00
2F-01-23	168+00	2031704	6675691	0.63	0.66	168+00
2F-01-26N	195+00	2028392	6675030	0.58	0.63	195+00
2F-01-30	217+00	2026688	6674746	1.32	1.37	217+00
2F-01-33	232+00	2024561	6674583	0.56	0.59	232+00
SRB-16	249+00	2022568	6673920	1.66	1.74	249+00
2F-01-36	271+00	2019733	6671964	1.26	1.28	271+00
2F-01-41	311+50	2016562	6668230	0.2	0.21	311+50
2F-01-46	369+00	2014262	6666773	1.64	1.73	369+00
2F-01-51N	394+00	2011639	6666035	1.22	1.23	394+00
2F-01-51N	394+00	2011639	6667053	1.22	1.23	394+00
2F-01-53	420+00	2008968	6667813	0.2	0.22	420+00
2F-01-54	438+00	2007547	6668892	0.68	0.75	438+00
2F-01-56N	466+76	2005770	6670729	1.19	1.29	467+00
2F-01-60	516+00	2002437	6674322	0.65	0.69	516+00
PZ-3	570+00	1998067	6676831	1.67	1.77	571+00
2F-01-66	592+00	1996292	6679133	1.59	1.71	592+00
2F-01-68N	611+56	1997685	6680572	1.14	1.21	611+00
2F-01-70	635+00	1998876	6682394	0.63	0.68	635+00
DH-7-3	662+00	1998368	6684874	0.35	0.38	662+00
2F-01-05S	679+40	1996993	6686228	1.31	1.36	678+00
DH-7-1	718+00	1993553	6686929	0.65	0.7	718+00
2F-01-15S	760+30	1988983	6687344	0.28	0.30	760+00
2F-01-19S	812+34	1984077	6688570	0.33	0.38	812+50
PZ-1	850+00	1981001	6690265	0.59	0.64	848+00
LMW-1	867+30	1980996	6692226	1.10	1.20	867+00



Well_ID	NLIPStatio	North	East	ie_100yr	ie_200yr	DWR_STA	Bulk_dens
2F-01-10N	42+00	2042370	6677161	0.32	0.33	42+00	1.5
2F-01-13	70+00	2041060	6677629	1.26	1.37	70+00	1.5
2F-01-04	84+00	2038313	6678021	0.8	0.9	84+00	1.5
2F-01-15N	98+30	2037443	6678210	0.55	0.58	91+00	1.5
2F-01-18	124+00	2035388	6677426	0.65	0.69	124+00	1.5
PZ-7	140+00	2033745	6676601	0.56	0.59	141+00	1.5
2F-01-23	168+00	2031704	6675691	0.63	0.66	168+00	1.5
2F-01-26N	195+00	2028392	6675030	0.58	0.63	195+00	1.45
2F-01-30	217+00	2026688	6674746	1.32	1.37	217+00	1.45
2F-01-33	232+00	2024561	6674583	0.56	0.59	232+00	1.5
SRB-16	249+00	2022568	6673920	1.66	1.74	249+00	1.5
2F-01-36	271+00	2019733	6671964	1.26	1.28	271+00	1.55
2F-01-41	311+50	2016562	6668230	0.2	0.21	311+50	1.55
2F-01-46	369+00	2014262	6666773	1.64	1.73	369+00	1.45

0

(0 out of 31 Selected)

Figure 5. Map showing data points related to SSURGO data (bulk density in gr/cm³).

$$\gamma_{sat} = \frac{\gamma_s + \gamma_w e}{1 + e}$$

where, γ_s is the moist unit weight of the soil, γ_w is the unit weight of the water equal to 1 gr/cm³ and, e is the void ratio which is a function of the porosity and can be computed as:

$$e = \frac{n}{1 - n}$$

Given that SSURGO data does not provide either void ratio or porosity information, this parameter has to be computed first in order to calculate the saturated unit weight. According to Vazquez-Amábile and Engel (2005), porosity can be approximated as a function of the bulk density as:

$$Porosity = 1 - \frac{bulk\ density}{particle\ density} = 1 - \frac{bulk\ density}{2.65}$$

where particle density has been generalized as 2.65 gr/cm^3.

A summary of the computations is presented as Table 3. Having the critical gradients and exit gradients near the levee system, provides enough information to analyze the stability with respect to the initiation of erosion. By means of GIS, an IDW interpolation was performed for 100-yr and 200-yr flood exit gradients and for the critical gradients as presented in Figure 6. With this interpolated data and using the Map Algebra/Raster Calculator, a factor of safety against the initiation of erosion was computed for 100-yr and 200-yr floods as shown in Figure 7. Since the computed FS outside of the leveed areas are unrealistic, an extraction by mask was done to only present FS surrounding the levee system as shown in Figure 8. Despite this being a good informative map, it is of greater interest to only show vulnerable areas with factors of safety less than 1.0. Due to this, another set of maps was created showing vulnerable areas as in Figure 9.

In view of the fact that it is of interest to show possible flooded depths of the Natomas Basin if a levee were to fail, Digital Elevation Model (DEM) data were downloaded from the National Map Viewer webpage. Using Map Algebra/Raster Calculator, different flooded depths were computed as shown in Figure 10. These flooded depths were superposed with the land use map shown in Figure 4 to show the most vulnerable areas.

Table 3. Computation of the critical gradients according to data points.

Well ID	Bulk density	Porosity	Void ratio	Sat density	i_c
2F-01-10N	1.5	0.434	0.767	1.934	0.934
2F-01-13	1.5	0.434	0.767	1.934	0.934
2F-01-04	1.5	0.434	0.767	1.934	0.934
2F-01-15N	1.5	0.434	0.767	1.934	0.934
2F-01-18	1.5	0.434	0.767	1.934	0.934
PZ-7	1.5	0.434	0.767	1.934	0.934
2F-01-23	1.5	0.434	0.767	1.934	0.934
2F-01-26N	1.45	0.453	0.828	1.903	0.903
2F-01-30	1.45	0.453	0.828	1.903	0.903
2F-01-33	1.5	0.434	0.767	1.934	0.934
SRB-16	1.5	0.434	0.767	1.934	0.934
2F-01-36	1.55	0.415	0.710	1.965	0.965
2F-01-41	1.55	0.415	0.710	1.965	0.965
2F-01-46	1.45	0.453	0.828	1.903	0.903
2F-01-51N	1.45	0.453	0.828	1.903	0.903
2F-01-51N	1.45	0.453	0.828	1.903	0.903
2F-01-53	1.5	0.434	0.767	1.934	0.934
2F-01-54	1.55	0.415	0.710	1.965	0.965
2F-01-56N	1.45	0.453	0.828	1.903	0.903
2F-01-60	1.5	0.434	0.767	1.934	0.934
PZ-3	1.5	0.434	0.767	1.934	0.934
2F-01-66	1.45	0.453	0.828	1.903	0.903
2F-01-68N	1.5	0.434	0.767	1.934	0.934
2F-01-70	1.5	0.434	0.767	1.934	0.934
DH-7-3	1.5	0.434	0.767	1.934	0.934
2F-01-05S	1.5	0.434	0.767	1.934	0.934
DH-7-1	1.5	0.434	0.767	1.934	0.934
2F-01-15S	1.5	0.434	0.767	1.934	0.934
2F-01-19S	1.45	0.453	0.828	1.903	0.903
PZ-1	1.5	0.434	0.767	1.934	0.934
LMW-1	1.5	0.434	0.767	1.934	0.934

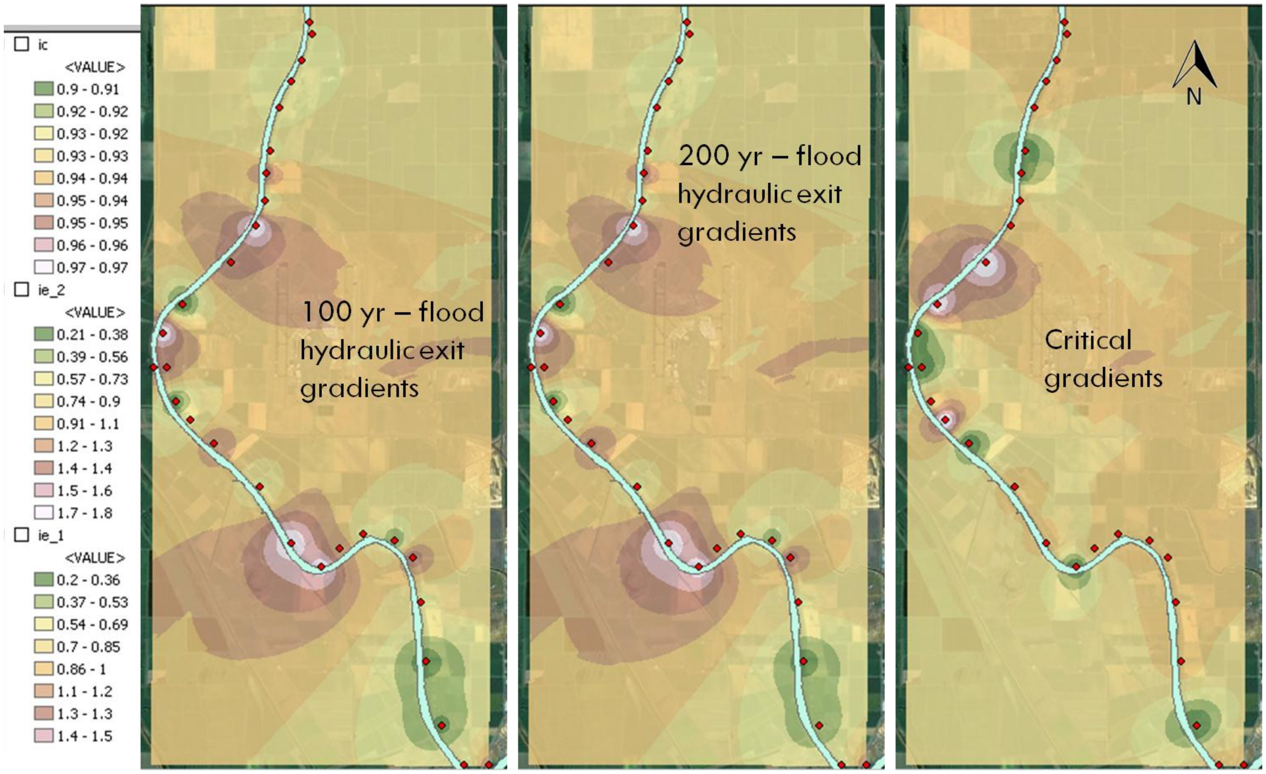


Figure 6. IDW interpolation for exit and critical gradients.

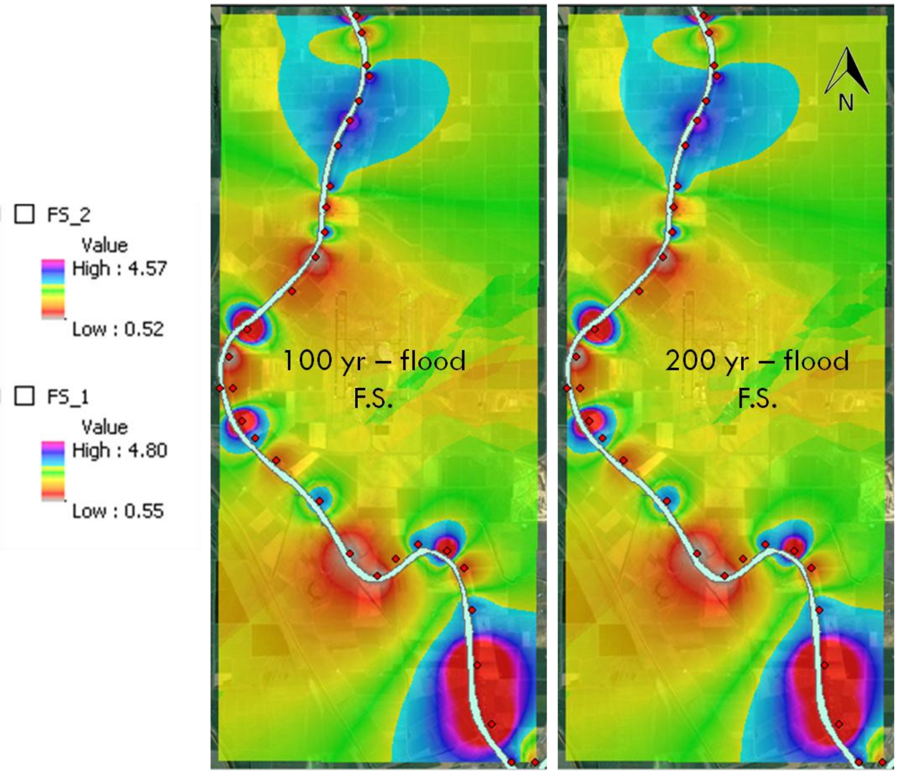


Figure 7. Calculated factors of safety against the initiation of erosion.

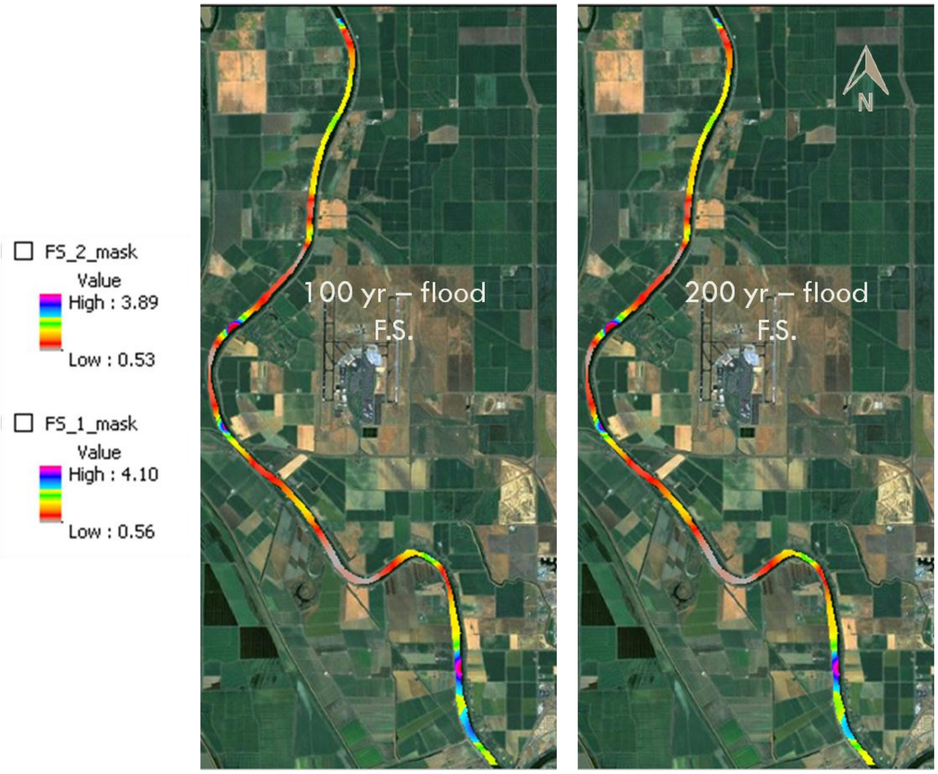


Figure 8. Extraction by mask of the factor of safety surrounding the levee system.

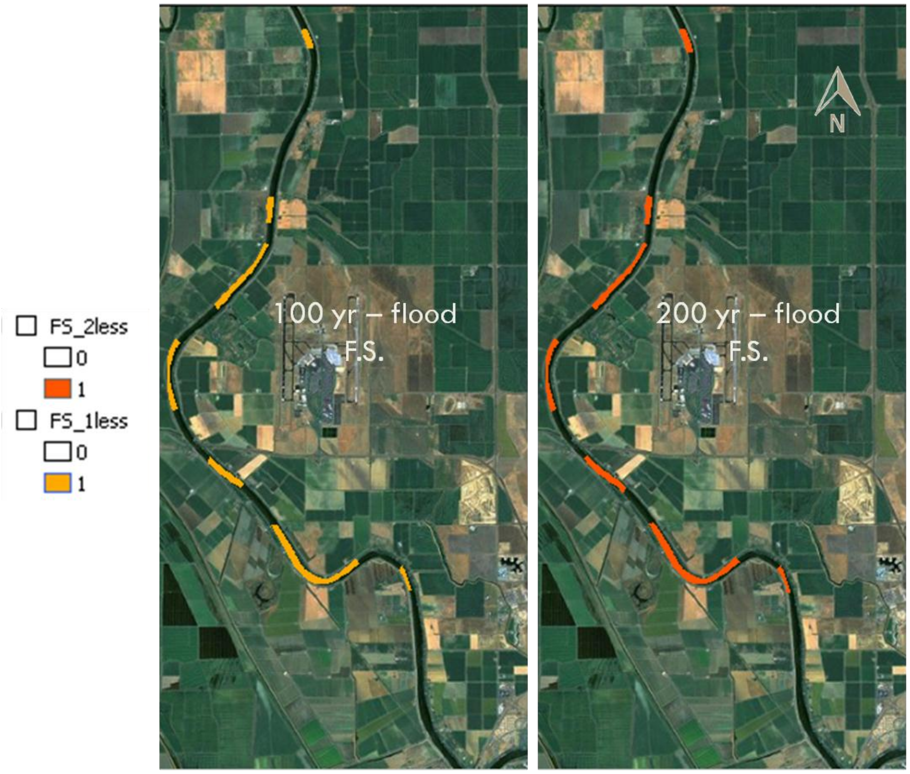


Figure 9. Vulnerable areas in the Sacramento River North, Natomas Basin.

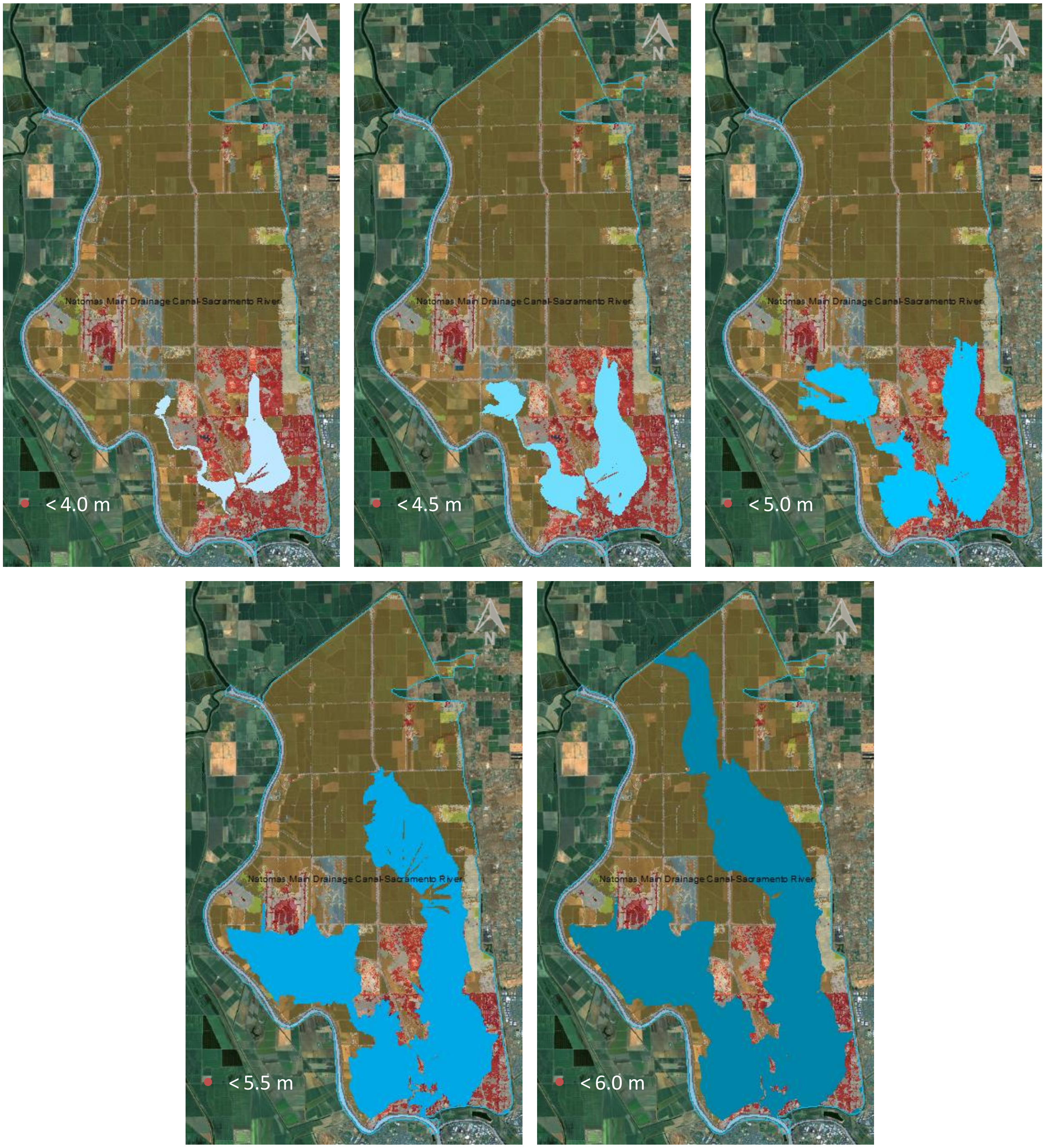


Figure 10. Possible flooded areas if a levee were to fail.

Summary and Conclusions

As it can be seen from Figure 9, vulnerable areas for 200-yr flood are very similar to the 100-yr flood as it is expected since the 100-yr flood is a subset of the 200-yr flood. In addition, it is important to notice that although there are very low computed factors of safety, this only represents the initiation of erosion which is considered to be the first phase in the development of the process of piping. Foster and Fell (2008) explain that it is helpful and practical to consider the failure mode process (in general) of internal erosion and piping into four phases: initiation of erosion, continuation of erosion, progression to form a pipe, and formation of a breach. These phases are represented in a sequence of events (event trees). The analysis presented herein represents one single node of the event tree. In order to assess failure, other points in the event tree will need to be assessed with calculations or by judgment.

It can be argued that the results of this analysis are questionable since we encounter very low factors of safety but it is reminded that this is only a pilot analysis and that factors of safety are a function of exit gradients hence, if a high exit gradient is computed, a low factor of safety will result for the corresponding computation. Also, the interpolation of exit gradients is not as accurate and surface soils were used instead of piezometric heads and sub-surface soils.

With respect to Figure 10 that shows possible flooded depths, it is interesting that the areas with the highest flooding risk are the developed areas at the South of the Natomas Basin. As a conclusion it can be said that GIS is a great tool to produce informative maps and compile data.

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