Quantifying the Impact of 20-Year Flood Frequency on Land Cover Change Type

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Abstract Flooding is the most common and destructive natural disaster in the United States. Ninety percent of all disasters in the US involve flooding, with impacts that cascade across the entire landscape. The primary objective of this study is to understand the impact of flooding on the landscape. One way to determine this is to observe the number of times a unit area of land is flooded and intersect that information with quantified changes in the landscape. The information for this analysis is derived from a complex workflow with inputs from large amounts of Landsat satellite imagery (more than 300 images) and multiple dates of land cover data from the USGS NLCD. The acquired NLCD data were used to generate from-to bivariate land cover change classes. A bivariate dataset was created for 5 date pair epochs. These classes were then used as zonal boundaries within which statistical variables were generated based on the flood frequency layer. By analyzing this information, we characterized what classes changed to what other classes given different frequencies of flooding. The area of interest for this study consists of one path row or footprint of a Landsat image on the border of Louisiana, Texas, and Arkansas near the city of Shreveport, Louisiana. This study area is known to have frequent flooding and a diverse landscape. During our analysis, we discovered that land cover changes in this study area more often occurred within areas that had flooded, rather than areas that had not flooded. Barren land cover change is clearly associated with flooding. Agricultural land changing to barren suggested that frequent flooding may cause arable land to not be as productive. When Barren land changes to vegetated cover and when Water changes to Barren, there is a strong likelihood that the change was due to flooding. Interestingly Urban land cover changes intersected with flood frequency regardless of the ratio. Over 2600 ha of Urban were built within the areas that have previously flooded. Some of the from-to change identified in this analysis was due to classification error, however this was minimized due to USGS's approach to land cover classification update, whereby only areas of change are classified. The results of this analysis are very useful for identifying where land cover change areas exist, their extent, and the likelihood they are associated with flood activity. This has implications and applications to flood plain management and community land use planning. The results of this study showed there is a relationship between some land cover change types and areas that frequently flood.

Keywords: remote sensing, GIS, land cover change, flooding, Landsat, bivariate analysis, floodplain management

Cite This Article: Francois G. F. Smith, and David J. Alexander, "Quantifying the Impact of 20-Year Flood Frequency on Land Cover Change Type." *American Journal of Civil Engineering and Architecture*, vol. 6, no. 1 (2018): 13-23. doi: 10.12691/ajcea-6-1-2.

1. Introduction

Flooding is the most common and destructive natural disaster in the United States. Ninety percent of all disasters in the US involve flooding with impacts that cascade across the entire landscape. While advances have been made in weather forecasting and watershed modeling to predict the future; it is still difficult to measure or characterize and assess the broad impact of flood inundation on the ground over a large area with historical context. In other words, there is a gap in our understanding of how land management is influenced by flooding over time. However, flooding can be quantified over time and space if you have access to satellite imagery at regular intervals.

The Landsat mission, having acquired data since 1972, and since 1982 at 30m resolution, affords researchers the ability to compile a backward looking dataset of change that can be combined with forward looking models to project future conditions.

The fusion of remote sensing and GIS has proven to be a valuable tool in land management and planning, enabling empirical observation of periodic changes in the surface of the earth for large areas over time [1,2,3]. This is especially important for long term community resilience planning and disaster risk mitigation, when it is necessary to understand past, present, and future conditions. This paper utilizes advances in satellite remote sensing and geospatial science to quantify the effect of frequent flooding on land cover over time using Landsat earth-observing data. More specifically, it explores how often a

selected study area floods, and what impact the frequency of flood events has on that landscape over a 20-year period using multi-date Landsat imagery and United States Geological Survey (USGS) National Land Cover Dataset (NLCD) data for the same area.

The contributions of this type of application has implications for public policy, community planning, and the practices of floodplain, storm water, and emergency management. It will produce an invaluable empirical (quantifiable) dataset that can be used to inform community mitigation and planning efforts - to improve our understanding of flood risk, and flood prone areas, and as an aid for prioritizing flood studies. With improved longitudinal understanding at the pixel level of flood risk, more empirical conclusions can be made on the impact of local land-use and economic development plans and infrastructure capacity. This understanding will also help us to:

1. Better understand the impact of frequent flooding on the landscape,
2. More logically predict what will happen to the landscape and how land is used in areas that flood multiple times, and
3. Ascertain how land cover will change over time as a response to climate change, as changes in weather patterns occur, flooding will likely occur in different frequencies and in new areas

2. Study Objective and Design

The primary objective of this study is to understand the impact of flooding on the landscape. One way to determine this is to observe the number of times a unit area of land is flooded and intersect that information with quantified changes in the landscape. If an area floods only once or twice in a decade, does the land cover change in a similar fashion as if it floods 100 times in a decade? Is there a correlation between how much an area floods and what type of land cover change occurs? Do these patterns of change occur consistently across decades? And finally are there specific types of land cover that are more prone to flooding?

In this study we intersected flood frequency data derived from satellite imagery with bivariate (from-to class) land cover change, which is also derived from satellite imagery. Five different epochs were tested:

- 2011 to 1992
- 2011 to 2001
- 2011 to 2006
- 2006 to 2001
- 2001 to 1992.

Flood frequency and land cover change were calculated for each of these date ranges. These two variables were intersected using a zonal majority function and tables were produced for analysis.

3. Data and Methods

Two datasets were acquired for this study, Landsat imagery and USGS NLCD land cover data. The 33+ year

archive of Landsat satellite imagery is the only source of systematic regular observations which may have captured a flood event. Approximately 20 years of Landsat imagery (ranging from 1984 to 2011) were compiled for the same scene footprint for the study area near Shreveport, Louisiana. Landsat 4-8 imagery ranging in dates of acquisition from 1984 to 2011 was downloaded and processed from the EROS Data Center. Over 300 scenes were downloaded, all of which cover the same footprint. A filter of <20% clouds was implemented. All images were corrected to account for astronomical and atmospheric factors that typically produce error in radiance values [4]. Clouds and cloud shadows were removed from all Landsat scenes. The images were then individually classified to produce binary water masks using a sophisticated water extraction algorithm. The flood extents were determined by direct detection of standing water and by inference from vegetation/soil stress due to soil saturation and observation post flood. The spatial extent of flooded areas was entirely based on satellite imagery observations. Flood frequency for each pixel was generated using the flood extent observations. The water masks were then stacked and the frequency of water inundation per pixel was calculated (0-100%). The stack of water masks were examined to determine the number of times each pixel had been inundated. Then the images were stacked according to the study time periods described in section 2 above. Frequencies were calculated for each of these date ranges. In order to analyze the impacts of flooding on land cover and land use, remote sensing change detection techniques were applied to the Landsat and NLCD data time series at 30-meters resolution. The process workflow is shown in Figure 1.

NLCD layers were also downloaded from the USGS. USGS NLCD land cover data was obtained for the same area for the target dates, 1992, 2001, 2006, and 2011. The NLCD is "a classification scheme based primarily on Landsat data along with ancillary data sources, such as topography, census and agricultural statistics, soil characteristics, wetlands, and other land cover maps" [5]. The NLCD provides researchers a consistent land cover classification scheme for the conterminous US at the same 30-m resolution as Landsat imagery. NLCD employs an approximately 20-class classification scheme (Figure 2).

The acquired NLCD data were used to generate from-to bivariate land cover change classes. A bivariate dataset was created for each data pair epoch listed above in section 2. A bivariate layer has a unique value for each possible from-to class permutation. Therefore there are n^2 number of bivariate classes where n = the number of classes in the original classification scheme. Our NLCD dataset contains 20 classes, therefore our bivariate layers contained 400 classes of from-to change. These classes were then used as zonal boundaries within which statistical variables were generated based on the flood frequency layer. By analyzing this information, we characterized what classes changed to what other classes given different frequencies of flooding. We also examined other statistics such as flood variability to understand its impact on land cover change. Finally we list the frequency of flooding for each of the NLCD categories in the study area.

Figure 1. Data Processing Workflow

Figure 2. NLCD: National Land Cover Dataset created for 4 epochs, by USGS

4. Study Area

The area of interest for this study consists of one path row or footprint of a Landsat image on the border of Louisiana, Texas, and Arkansas near the city of Shreveport, Louisiana. (Figure 3). The area covers a little over 2.5 million hectares and is a fairly diverse landscape. It also contains the Red River which has flooded many times over the last 30 years. The Red River is the second largest river basin in the southern Great plains, and its watershed covers 65,590 square miles (169,900 km²) [6]. (Figure 4) The sister cities of

Shreveport and Bossier City lie on either bank of the Red River after it crosses south into Louisiana. Even farther downstream, the Red River connects to the Mississippi river by the Old River control structure, where it becomes the Atchafalaya River before flowing into the Gulf of Mexico [6]. The Old River control structure was completed by the US Army Corps of Engineers in 1963 to regulate the flow of water between the Mississippi river and the Atchafalaya River [7]. (Figure 5). During this downstream journey, the Red River watershed transitions from pine forests and agricultural land into effusive marshland [7].

Figure 3. Study Area: Red River near Shreveport, La

Figure 4. Red River Watershed

Figure 5. Old River Control Structure (Courtesy of US ACE 2014)

The Shreveport area has a humid subtropical climate with average normal annual precipitation over 51 inches (1.3 m), and monthly totals ranging from 5 inches (130 mm) in June to 3 inches (76 mm) in August. During the spring and summer months, the region is plagued by severe thunderstorms with heavy rain, hail, damaging winds and tornadoes. (NWS 2017). While historically prone to riverine flooding, the study area has experienced an increasing number of floods related to heavy precipitation rainfall events or flash floods likely attributable to land-use changes and urbanization. The Shreveport-Bossier Metro region is the commercial and cultural center where the three states of Texas, Arkansas, and Louisiana meet [8]. According to the US Census, in 2010, the population in the Shreveport metro region exceeded 411,000, a 323% increase from when it was established in 1950 (pop. 126,206).

5. Analysis

In Figure 6, you can see a subset of the study area that is focused on a portion of the Red River in the north. This figure depicts the percent flood frequency layer overlaid on a raw Landsat image from the time series. The color ramp bar on the right side shows the continuum of frequency of water calls in the stack of imagery. Red means a pixel was only called water once in the entire stack and magenta means the pixel was called water in every scene in the stack of images. A “permanent” water feature such as a lake is depicted as magenta. All of the colors in between represent pixels that are intermittently inundated with water a various number of times. The maximum extent of a one-time major flood would appear as red. Figure 7 shows another portion of the study area near Millwood Lake. In this figure, Millwood Lake is depicted as magenta. Several areas in the left quadrant of the image are red suggesting one-time flood events. Figure 8 shows the land cover change for the same portion of Red River in the north of the study area depicted in Figure 6. Similarly, Figure 9 shows the land cover change for the portion of the study area near Millwood Lake depicted in Figure 7.

The zonal majority intersection process was performed on each of the 5 ranges of dates of the datasets described

in section 2. The process resulted in a series of tables (Table 1 - Table 5). The first column shows the from-to bivariate change class. The second column shows the ratio of flood to non-flood pixels. This is the number of pixels that changed within areas that flooded divided by number of pixels that did not flood. This ratio represents how many times we observed this from-to change type within flood areas as opposed to outside observed flood areas. If this ratio is higher than a value of 1, then it occurred more times within areas that flooded than areas that did not flood. The higher the value, the more related to flooding that change type is. The third column shows the number of hectares covered by that bivariate class, and the fourth column is the same area but represented in pixels. The following columns are all percents of observed water frequency. These tables represent up to 15% flood frequency because that is the range where the more catastrophic flooding occurs, but the analysis includes up to 50%. Beyond 50% we are more likely dealing with seasonal water inundations rather than floods.

First we looked for a higher ratio of flood pixels to non-flood pixels in the table and if they covered a significant number of hectares, a red box was placed around these classes in the tables. This is the number of pixels that changed within areas that flooded divided by the number of pixels that did not flood. For this study we are looking only at pixels where a change type occurred more times in areas that flooded than in areas that did not. The higher the ratio (in the second column), the more likely the change type is flood induced, we are defining flood induced change as changes that happened more often within flooded areas than outside of flooded areas. For this analysis, frequently flooded areas were defined as areas that are observed as flooded more than once in the 20-year dataset (1984 to 2011). Inundations occurring in more than fifty percent of the observations were considered “permanent” water (Inundation occurring > 50%). Inundations occurring in greater than one percent and less than or equal to fifty percent of the observations were considered “intermittent” or flooded water (Inundation occurring > 1% and <=50%). Tables for the five date pairs were summarized to show only results where the ratio was greater than one (ratio (R) > 1). The resulting tables (five sets) were then analyzed and interpreted.

Figure 6. Example of Flood Inundation Layer for the Study area in north portion of the Red River

Figure 7. Example of Flood Inundation Layer for the study area near Millwood Lake

Figure 8. Land cover change for the Study area in north portion of the Red River

Figure 9. Land cover change for the Study area near Millwood Lake

Table 1. 1992-2001 Flood Frequency Impact on Land Cover, Summarized Table

<i>Bivariate Change Classes 1992-2001</i>	Ratio of flood pixels to non-flood	Hectares	<i>Total Pixels</i>	0	<i>Observed Water Frequency %</i>															
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
Forest Deciduous to Water	1.758747842	2017.53	35163	12746	3023	3310	2515	2468	1747	1647	1519	1300	949	901	763	715	583	488	489	
Forest Evergreen to Water	1.488597898	1503.99	27937	11226	2493	2637	1868	1747	1313	1087	1175	757	670	646	585	508	447	399	379	
Barren Sparsely Vegetated to Water	0.894554883	93.15	2192	1157	174	195	106	85	74	56	53	43	46	40	36	29	30	33	35	
Urban to Water	0.840909091	6.66	162	88	11	11	9	13	6	7	2	1	5	1	2	0	4	1	1	
Agriculture (Other) to Barren/Sparsely Vegetated	0.482148401	139.77	4774	3221	221	211	188	141	113	100	95	82	59	66	73	53	57	37	57	
Agriculture (Other) to Water	1.786625933	2368.53	41047	14730	3131	2749	2161	2997	1961	1923	1725	1890	1440	1340	1228	1112	1030	836	794	
Wetlands/Salt Pans to Barren/Sparsely Vegetated	0.670995671	13.95	386	231	27	25	10	8	9	4	10	7	7	15	7	3	9	9	5	
Wetlands/Salt Pans to Water	1.985254377	3041.37	50815	17022	3927	5457	4617	4021	3293	2593	2182	1862	1332	1168	954	707	629	551	500	
Water to Forest Deciduous	0.953784519	599.94	13655	6989	878	688	537	481	439	385	367	379	373	400	327	340	434	325	313	
Water to Forest Evergreen	0.587421268	1149.93	34528	21751	2832	1762	1192	932	784	701	664	551	567	602	531	440	421	363	435	
Water to Scrub/Shrub	0.49222395	284.85	9595	6430	493	398	274	211	209	171	190	175	150	151	170	154	158	122	139	
Water to Grassland	1.053097345	10.71	232	113	9	5	2	6	7	7	9	14	17	8	3	10	12	7	3	
Water to Barren/Sparsely Vegetated	23.48192771	175.41	2032	83	18	34	52	47	76	87	76	110	132	163	183	160	205	284	322	
Water to Agriculture (Other)	1.971441061	1217.7	20393	6863	1558	1212	998	1031	969	844	786	775	786	863	838	774	760	690	646	
Water to Wetlands/Salt Pans	2.110149489	965.52	15812	5084	1556	1290	972	804	759	660	586	596	502	558	462	484	512	488	499	

Table 2. 2001-2006 Flood Frequency Impact on Land Cover, Summarized Table

<i>Bivariate Change Classes 2001-2006</i>	Ratio of flood pixels to non-flood	Hectares	<i>Total Pixels</i>	0	<i>Observed Water Frequency %</i>														
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Forest Deciduous to Water	1.911242604	87.21	1476	507	0	87	24	32	39	15	17	23	25	8	19	27	16	11	22
Forest Evergreen to Water	1.96043956	80.28	1347	455	0	92	33	27	43	25	19	32	21	17	15	20	7	21	23
Scrub/Shrub to Water	3.44295302	92.34	1324	298	0	78	36	28	32	15	11	26	18	13	24	13	20	20	21
Grassland to Water	5.166666667	2.79	37	6	0	4	0	5	1	0	1	0	0	0	0	0	1	0	1
Barren Sparsely Vegetated to Forest Deciduous	2.615384615	9.18	141	39	0	8	5	1	2	0	0	0	0	1	1	0	1	1	1
Barren Sparsely Vegetated to Forest Evergreen	1.157772622	44.91	930	431	0	47	1	30	30	8	17	19	17	16	25	15	19	16	16
Barren Sparsely Vegetated to Scrub/Shrub	4.923076923	28.8	385	65	0	22	0	18	11	1	5	4	4	11	19	8	13	8	8
Barren Sparsely Vegetated to Grassland	10.43589744	36.63	446	39	0	17	4	24	11	5	12	2	2	7	5	9	10	5	10
Barren Sparsely Vegetated to Agriculture (Other)	1.11627907	17.28	364	172	0	33	2	8	8	1	8	3	0	2	5	2	6	4	2
Barren Sparsely Vegetated to Wetlands/Salt Pans	30.44444444	49.32	566	18	0	36	8	2	14	7	11	31	30	17	11	14	13	15	8
Barren Sparsely Vegetated to Water	17.40677966	92.43	1086	59	0	24	0	19	13	2	17	5	5	17	8	13	6	5	7
Agriculture (Other) to Water	6.577540107	442.8	5668	748	0	183	78	62	127	67	59	98	60	69	68	65	63	99	84
Wetlands/Salt Pans to Agriculture (Other)	1.631051176	424.53	7609	2892	0	263	62	147	211	38	254	180	37	155	130	51	127	100	76
Wetlands/Salt Pans to Water	1	89.01	1978	989	0	100	20	18	34	10	20	20	13	12	20	11	12	12	31
Water to Forest Deciduous	3.181818182	9.45	138	33	0	14	3	2	6	6	3	2	4	2	1	2	1	2	2
Water to Forest Evergreen	1.934235977	90	1517	517	0	153	29	55	48	21	41	29	24	26	14	21	12	17	10
Water to Scrub/Shrub	6.339285714	223.65	2877	392	0	87	10	39	51	17	38	38	22	40	35	22	54	43	44
Water to Grassland	7.795803067	1738.62	21796	2478	0	1049	328	942	828	348	579	551	321	505	434	330	504	351	401
Water to Barren/Sparsely Vegetated	33.21066667	1120.86	12829	375	0	144	47	45	73	38	71	129	44	140	78	110	106	62	91
Water to Urban	1.84	20.7	355	125	0	25	12	4	5	8	3	2	3	1	0	7	2	1	4
Water to Agriculture (Other)	4.055555556	19.71	273	54	0	10	7	3	4	1	4	4	0	3	7	1	3	1	0
Water to Wetlands/Salt Pans	17.88744138	3089.34	36245	1919	0	777	368	787	780	356	496	621	404	526	479	392	594	497	498

Table 3. 2006-2011 Flood Frequency Impact on Land Cover, Summarized Table

<i>Bivariate Change Classes 2006-2011</i>	Ratio of flood pixels to non-flood	Hectares	Total Pixels	<i>Observed Water Frequency %</i>																
				0	1	2	3	4	5	6	7	8	9	#	#	#	#	#	#	#
Forest Deciduous to Water	4.110465116	63.63	879	172	0	50	0	29	0	13	1	15	4	11	7	2	9	7	10	
Forest Evergreen to Water	3.775700935	72.72	1022	214	0	45	0	28	1	29	1	24	9	13	5	12	19	12	8	
Scrub/Shrub to Water	6.383116883	88.47	1137	154	0	32	1	22	0	16	4	17	2	13	6	2	7	4	3	
Grassland to Wetlands/Salt Pans	1.114355231	41.22	869	411	0	52	0	31	0	46	3	23	7	6	7	5	3	2	9	
Grassland to Water	15.5	200.88	2376	144	0	51	1	36	0	21	4	23	7	21	11	17	14	13	10	
Barren Sparsely Vegetated to Grassland	1.083832335	16.29	348	167	0	6	0	39	0	7	1	6	7	14	10	1	3	2	1	
Barren Sparsely Vegetated to Wetlands/Salt Pans	11	2.97	36	3	0	0	0	2	0	0	0	2	0	4	3	4	1	0	3	
Barren Sparsely Vegetated to Water	62.5	157.5	1778	28	0	14	0	5	0	6	1	4	5	1	6	3	3	1	5	
Agriculture (Other) to Water	9.676056338	185.49	2274	213	0	121	1	63	1	53	11	39	24	21	38	44	60	69	25	
Wetlands/Salt Pans to Water	3.576923077	8.37	119	26	0	8	0	3	0	5	0	1	1	1	2	2	2	2	1	
Water to Forest Deciduous	6.565217391	108.72	1392	184	0	47	1	26	1	23	0	14	8	7	9	7	13	11	13	
Water to Forest Evergreen	4.18630137	137.52	1893	365	0	50	1	40	0	22	2	16	6	15	15	5	10	1	8	
Water to Scrub/Shrub	11.61863354	841.77	10158	805	0	180	12	101	10	75	15	87	40	50	49	26	63	38	43	
Water to Grassland	4.88589398	489.42	6551	1113	0	248	1	155	4	125	10	127	56	83	84	58	74	49	75	
Water to Barren/Sparsely Vegetated	39.07619048	738.54	8416	210	0	40	2	31	4	28	4	16	14	17	27	10	30	7	29	
Water to Urban	1.935483871	16.2	273	93	0	20	0	15	0	5	0	3	1	3	0	2	0	5	1	
Water to Agriculture (Other)	3.071625344	100.35	1478	363	0	23	1	22	0	23	2	16	5	13	3	10	17	8	10	
Water to Wetlands/Salt Pans	13.2887538	393.48	4701	329	0	56	0	28	1	19	1	20	9	14	16	7	10	13	13	

Table 4. 2001-2011 Flood Frequency Impact on Land Cover, Summarized Table

<i>Bivariate Change Classes 2001-2011</i>	Ratio of flood pixels to non-flood	Hectares	Total Pixels	<i>Observed Water Frequency %</i>																
				0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	
Forest Deciduous to Water	3.53831418	166.23	2369	522	120	71	45	31	28	33	32	29	28	34	18	25	34	23	24	
Forest Evergreen to Water	3.86796117	179.28	2507	515	127	64	63	52	45	27	41	36	33	33	33	36	37	33	27	
Scrub/Shrub to Water	6.44267516	182.07	2337	314	84	53	22	29	19	21	19	15	10	29	24	23	22	23	27	
Grassland to Water	5.54545455	5.49	72	11	1	2	0	1	2	0	0	1	1	0	1	1	0	0	0	
Barren Sparsely Vegetated to Forest Deciduous	2.58974359	9.09	140	39	9	5	3	0	0	1	0	2	2	0	1	0	3	0	0	
Barren Sparsely Vegetated to Scrub/Shrub	7.34328358	44.28	559	67	21	21	10	8	14	8	14	25	13	10	14	22	24	16	23	
Barren Sparsely Vegetated to Grassland	10.106383	42.75	522	47	18	13	7	10	8	23	12	15	12	10	6	11	13	22	13	
Barren Sparsely Vegetated to Agriculture (Other)	1.10326087	18.27	387	184	32	8	7	7	3	6	3	3	3	3	2	3	6	5	5	
Barren Sparsely Vegetated to Wetlands/Salt Pans	31.5	51.03	585	18	36	9	10	11	25	17	12	19	21	18	29	17	27	21	23	
Barren Sparsely Vegetated to Water	43.2258065	120.6	1371	31	7	2	9	3	3	3	5	7	6	6	6	4	4	6	7	
Agriculture (Other) to Water	9.54065621	601.92	7389	701	215	133	105	98	77	126	190	127	109	104	87	82	92	76	87	
Wetlands/Salt Pans to Barren/Sparsely Vegetated	1.42990654	27.54	520	214	57	18	17	13	11	7	11	7	6	9	6	9	7	10	4	
Wetlands/Salt Pans to Agriculture (Other)	1.85881908	441.99	7553	2642	177	143	169	194	149	163	156	182	175	176	132	142	118	95	111	
Wetlands/Salt Pans to Water	1.75198728	99.18	1731	629	91	31	20	12	19	15	10	9	18	9	12	15	8	16	16	
Water to Forest Deciduous	14.2058824	130.41	1551	102	29	15	12	13	14	16	15	16	9	12	16	8	14	12	11	
Water to Forest Evergreen	4.4787234	265.23	3605	658	182	116	60	110	52	45	46	30	33	38	24	33	29	21	24	
Water to Scrub/Shrub	16.2553191	1237.68	14598	846	268	140	140	124	124	113	89	90	100	108	72	88	85	83	85	
Water to Grassland	7.66381236	1852.65	23271	2686	1174	1204	874	823	652	629	555	515	463	533	389	441	450	379	398	
Water to Barren/Sparsely Vegetated	38.5321285	1727.01	19687	498	171	80	83	102	130	148	109	87	63	60	51	81	105	76	105	
Water to Urban	2.92307692	44.46	663	169	57	22	14	14	9	10	9	7	14	7	7	12	4	7	7	
Water to Agriculture (Other)	4.33544304	123.3	1686	316	70	25	16	19	12	12	12	14	12	11	16	18	10	11	9	
Water to Wetlands/Salt Pans	20.5403564	3527.19	41099	1908	844	1016	838	790	679	711	619	708	708	691	590	556	522	427	457	

Table 5. 1992-2011 Flood Frequency Impact on Land Cover, Summarized Table

Bivariate Change Classes 1992-2011	Ratio of flood pixels to non-flood	Hectares	Total Pixels	0	Observed Water Frequency %														
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Forest Deciduous to Water	4.105095541	3132.27	43281	8478	6851	4591	2471	1663	1422	1189	910	882	802	754	602	533	568	515	509
Forest Evergreen to Barren/Sparsely Vegetated	1.136511376	566.46	11832	5538	4360	524	240	207	127	93	83	69	54	54	30	31	34	39	27
Forest Evergreen to Water	3.973054367	2255.94	31375	6309	6573	3462	1720	1346	1066	957	783	700	661	564	470	452	419	378	322
Barren Sparsely Vegetated to Water	4.33875	312.39	4271	800	412	216	111	106	63	67	60	58	54	53	41	50	52	35	43
Urban to Water	3.189655172	16.65	243	58	32	16	9	7	2	4	5	3	0	3	3	2	2	2	0
Agriculture (Other) to Water	5.246142542	4498.2	59507	9527	5577	4176	3015	2298	1944	1516	1382	1307	1442	1274	979	979	883	873	884
Wetlands/Salt Pans to Barren/Sparsely Vegetated	1.573216521	113.13	2056	799	330	102	45	52	19	32	23	23	13	12	20	11	13	10	14
Wetlands/Salt Pans to Water	4.165457333	3668.31	50544	9785	11071	7235	3499	2350	1950	1455	1041	903	811	703	605	514	453	416	385
Water to Forest Deciduous	3.090839304	1087.11	15987	3908	2789	762	461	432	449	367	370	504	450	385	323	249	210	196	186
Water to Forest Evergreen	3.143694723	2847.15	41698	10063	11141	2480	1110	1003	803	665	581	547	517	467	394	373	372	341	348
Water to Scrub/Shrub	5.362934363	2000.16	26368	4144	2785	637	300	322	255	200	201	208	190	172	204	166	175	144	164
Water to Grassland	12.91829356	1607.94	19249	1383	1376	450	239	228	205	198	213	218	246	208	194	186	170	189	211
Water to Barren/Sparsely Vegetated	138.1576577	2760.39	30893	222	90	57	35	64	60	69	87	111	158	198	202	247	327	349	394
Water to Urban	1.477692526	468	8719	3519	1926	271	127	113	84	64	66	57	62	55	48	46	48	55	37
Water to Agriculture (Other)	5.810555675	2437.47	31744	4661	3010	1459	742	909	761	660	655	616	587	647	640	649	762	888	847
Water to Wetlands/Salt Pans	23.56200747	5112.72	59219	2411	3411	2243	1224	1231	1056	910	842	793	720	705	625	620	585	616	577

6. Results and Discussions

When analyzing the summarized tables, we discovered that land cover changes more often occurred within areas that had flooded (pixels that had a ratio > 1); rather than, areas that had not flooded. These results are shown in Table 1. Water changing to Barren provided an indication of land that had flooded. Agriculture changing to barren suggested that frequent flooding may cause arable land to not be as productive. The urban to water change was a bit surprising and also important to note, even though it is a very small amount of change over the 2.5 million ha study area. Table 2 shows the results of the comparison of land cover change and flood frequency both between the years of 2001 and 2006. This time period also showed that Barren land cover change is highly correlated to flooding in this study area. When Barren land changes to vegetated cover and when Water changes to Barren, there is a strong likelihood that the change was due to flooding. For this date pair, we notice some previously called Water pixels have become Urban pixels. This change type occurred almost twice as often in areas that have flooded. This discovery was very interesting because it suggests that there is new Urban growth in flooded areas, albeit only about 21 ha. Table 3 shows similar results for the comparison of land cover change and flood frequency for

the 2006-2011 date period. Barren changed to some classes, Water changed to Barren within the flood areas, and Water changed to Urban in a small area. This pattern continues for the date period 2001-2011. Table 4 depicts the results of the comparison of land cover change and flood frequency between the years of 2001 and 2011. Comparing the land cover change and flood frequency for the date pair 1992 and 2011, representing the entire time span confirmed that Barren land cover change is associated with flooding (Table 5). The results for this date pair also showed that almost 470 ha of Water turned to Urban.

After analyzing all the date pairs, we found that Urban land cover changes intersected with flood frequency regardless of the ratio. Table 6 shows the results of all Urban land cover change between 1992 and 2011 intersected with flood frequency regardless of the ratio. This table suggests, since the ratios are mainly very low, that most Urban change is not associated with flood. It also appears that lots of Evergreen Forest was harvested and replaced by Urban, but not in the flooded areas. To better understand this Urban land cover change, we compiled data to show Urban gains and losses within the flooded areas for date pair 1992-2011. Table 6 depicts the results of this comparison and shows that over 2600 ha of Urban were built within the areas that have flooded. This is much more substantial than the amount of Urban loss.

Table 6. Urban Gains and Losses in Frequently Flooded Areas, 1992 – 2011

1992 - 2011 Urban Results	Acres	Percent of Total Urban inside frequently flooded areas	Percent of Total Urban in the Study Area
Urban loss inside areas that have flooded	208.89	1%	0%
Urban gain inside areas that have flooded	26513.37	85%	15%
Urban no change in areas that have flooded	4089.96	13%	2%
Total Urban inside frequently flooded areas (2011)	31194.36		
Total Urban in the Study Area (2011)	179615.7		

There was a substantial net gain in Barren features in each of the date pairs tested, and 2760 ha gain in Barren features over the entire study time period. Barren changed in flooded areas much more than it changed outside of the flooded areas. There was ~566 ha of forest that changed to Barren land cover, which is more than happened outside the flooded areas. This is probably due to harvesting of trees in the flood plain, but could also be due to damage to forests by flooding. Nearly twice the amount of Agriculture was lost to Water (~4500 ha) as was gained from Water (2437 ha) during the full study period. In every date pair, in flooded pixels, there was some Water which changed to Urban, usually around 16 ha, except between 2001 and 2011, when there was 44 ha of Urban growth. Over the entire study period, there was a loss of ~17 ha of Urban features to Water, but this was outweighed by the gain in Urban from Water (468 ha). The only Urban change that appears significantly due to flooding was Urban to Water or Water to Urban. According to this data, as of 2011, 85% of the Urban features within the frequently flooding areas were built between 1992 and 2011.

Of course, some of the change identified in this analysis was invariably due to classification error. This is probably more acute in the 1992 dataset, which is less accurate than later datasets [9]. The NLCD accounts for most error in the other datasets by implementing a change-based land cover update approach. Starting from 2001, the USGS began implementing a method of land cover update whereby they re-classified only areas of change, thus increasing compatibility among the different years of the NLCD datasets for change analysis, and mitigating classification error as a factor [10,11]. This update approach results in the NLCD having a general accuracy of 80% overall and per class per pixel [12]. Any NLCD classification error for this study was likely limited to around 5-10%.

Regardless of the potential classification error, this data indicates there are new urban features being constructed, and built within flooded areas.

7. Conclusions

The results of this analysis are very useful for identifying where these areas exist, how many areas, and the likelihood they are associated with flood. This has implications and applications to flood plain management and community land use planning. Demonstrating the accuracy of the flood identification methods from historical Landsat data, allowed us to analyze the flooded pixels against land cover, to better understand settlement patterns in relation to flood risk over time, as a proxy for local land use practices and planning. It provided both empirical data based on observation and quantifiable information on potential risk related to settlement patterns in a community. Combining this with the FEMA Special Flood Hazard Areas (SFHA) information and National Flood Insurance Program (NFIP) claims data would furnish floodplain managers with enhanced capacity to prioritize flood studies, investigate nontraditional flood prone areas, and inform more immediate and long term community mitigation and planning decisions.

There are many other ways to analyze the data from this study; our method was just one approach. The results of this study showed there is a relationship between some land cover change types and areas that frequently flood. It also indicated what change types of land cover change occurred. The Barren Class was the most impacted by flooding. Barren often changed to other vegetated categories in pixels that had flooded multiple times. Any gain in Urban land cover type, within the areas of frequent flooding, around the Red River should be investigated. This land use change indicates building in flood prone areas during the period of study. This study maps those locations. Pixels showing a loss of Urban should also be investigated to discern whether this is classification error or does it represent total destruction of urban structures from flooding. Since there were so few pixels, a number within margin of error, it could be just classification error.

Research of this nature should be done for many different geographic areas in order to understand the variability of flood frequency impact on land cover across the nation. It could also help ascertain if there are regional trends in impact. For example, the sources of flooding are different in coastal environments versus inland flood plain environments, so impact on land cover class change may be different. Other analyses could also be done using this data. We looked at any percent inundation > 0, but maybe specific quantities of inundations correlate to specific land cover change. Additional research could be done to validate and quantify the accuracy of the study results, by tracking changes in the imagery with the flood data. More analysis could be done focusing only on Urban change in the frequently flooded areas for each of the date pairs to determine more precisely the range of dates of when new construction occurred.

Acknowledgments

We would like to acknowledge Flood APEX program within the Science and Technology Directorate of the U.S. Department of Homeland Security for supporting this research project. We would also like to acknowledge the USGS EROS Data Center for use and pre-processing of Landsat images and also for the USGS NLCD classification datasets.

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