IDENTIFYING OIL SPILL HAZARDS IN NORTH DAKOTA, THROUGH HYDRAULIC MODELING AND CONSERVATION PLANNING

SONG,YANG
North Dakota State University, y.song@ndsu.edu

DAVIS-KOLLMAN, MORGAN
North Dakota State University, morgan.daviskollma.1@ndsu.edu

1 ABSTRACT

North Dakota is the second largest in oil production in the United States with 85 paramount oil spills within the last 20 years. In 2006, a broken pipeline burst more than a million gallons of brine wastewater into Charbonneau Creek in Northwestern North Dakota, altering ecosystem services and the residents who relied on the land and surrounding water bodies. The massive die-off of fish, plants and the tainting of productive soil and drinkable water sources especially for Native Americans who are most reliant on environmental healthy and stability.
Oil spills are extremely unpredictable, with little available information of when, where and how they occur. Beyond the unforeseeable, there are few remediation or planning strategies to be executed when spills transpire. While most literature focuses on the reporting protocol and response actions, this study will propose an analytical strategy to estimate the environmental threat of oil spills to water resources through environmental planning. Geospatial and hydraulic modeling tools will be introduced using USGS StreamStats for watershed-based drainage delineations, basin characteristic visualization, and streamflow estimation. Impacted landuses will be examined and analyzed to inform environmental intervention. The result will present an efficient framework for hazard identification, vulnerability analysis and ecological planning for an endangered watershed area on Fort Berthold Reservation. The goal is to produce new perspectives on possibilities of creating a more resilient and sustainable tribal community.

1.1 Keywords

Geographic Information System, Hazard identification, Oil Spill, Conservation Planning

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2 INTRODUCTION

North Dakota state is ranked number two in US in oil production, just behind the state of Texas, producing 1.3 million barrels of oil per day (Crude oil production, 2017). Approximately 1.4 million crude oil with regulated hazardous liquid run with pipelines across the state, with loose regulations on oil spill reporting (David, 2016; Oil Transportation Table, 2018). However, the state does not require that the public be notified in the event of an oil spill, making it a closed-door industry. Research in many regions throughout the nation have shown that contamination from fracking has been fairly sporadic and inconsistent; in North Dakota it is widespread and persistent, with evidence of direct water contamination from fracking (Daniel, 2016). A recent analysis from 2013-2017 found that 42% of oil and 57% of brine spilled was uncontained, spewing nearly 37,000 barrels of oil and over 169,000 barrels of toxic saltwater. Lack of regulation and expansion of industry has enabled an average of 4.4 spills a day across the state since 2013(Springer,2016).

2.1 Environmental hazard within the pipeline oil spill

Pipeline spills are releasing toxins into soils and waterways at alarming rates, exceeding the nation's water quality standards (Scientists Say Oilfield, 2016). One gallon of wastewater or oil can make nearly a million gallons of freshwater undrinkable (Office of Research and Development, 2016). This improper disposal of these contaminants percolate and infect the groundwater, damage surface soil, water resources and inhabitants of the affected area. With increased implementation of wells and pipelines, the number of spills and leaks have followed. In the United States on average, from 1986-2013, one significant oil or gas pipeline incident occurred every thirty hours (Daniel, 2016). Spills and pipeline failures transpire in a variety of ways such as mechanical failure, human error and/or subfreezing temperatures which cause ruptures within the system (Pipeline Risks, 2017). The implementation of metals into water sources inhibits carbon, sulfur and phosphorus mineralization and nitrogen transformations, hindering photosynthesis and reproduction cycles. Due to the rise in spills, corruption of natural resources has multiplied. Only about 20% of oil compounds degrade within water, revealing 35x the level of ammonium and selenium in sampled water that the United States Environmental Protection Agency considers safe for freshwater aquatic life and use (Office of Research and Development, 2016).

2.2 Fort Berthold reservation

The increase of oil rigs and pipeline development across the Western part of North Dakota have led to detrimental impacts within Native American reservations. Most of them do not benefit from oil discovery and extraction financially and many times suffer environmentally which influence their vital farming and ranching practices. Fort Berthold is one reservation within the Bakken, with tribal land being owned by Native American as individual allotments or communally by the tribe (Three Affiliated, 2016). As of March 2016, 15,013 registered tribe members were reported (Demographics | North, 2016). This tribal land is subjected to serious threats from oil industry since North Dakota Department of Health revealed more than 8,000 spills [both pipeline and rigs] were recorded from 2008 to 2015 in the region (Cozzarelli et al, 2017). Due to the economic downward spiral, the unemployment rate has reached an alarming 26.5 percent, leaving approximately 750 workers to support 6,000 tribal residents. Centuries of treaties have resulted in the confiscation of large portions of land from the reservation and lack of economic stimulation. The implementation of the oil industry since the Bakken Boom has caused further hardship on surrounding Native American communities and their daily environment (Thompson, G, 2016).

2.3 Oil spill contingency planning and environmental planning

Most of the current effort on oil spills are based around the containment and recovery, focusing on the techniques after the oil spill event. Typical strategies include the use of booms, skimmers, sorbents or in-situ burning and other specifics (Oil Program Center, 1999, p9-18). The Environmental Protection Agency (EPA) has also specified a contingency plan for preparing oil spills events which consist of hazard identification, vulnerability analysis, risk assessment the use and response action. However, this contingency plan does not provide environmental planning guidance but "like a 'game plan,' or a set of instructions that outlines the steps that should be taken before, during, and after an emergency" (Oil Program Center, 1999, p27).

Environmental planners perform duties lie (March 2010, p24) hazard assessment which specifically aim for identifying vulnerable areas in environments where an industrial use exists and would risk damage to occur. Risk Management involves building strategies dealing with hazards and providing emergency relief services. Both Hazard Assessment and Risk Management planning started gaining serious attention to issues such as storm surge, riverain flooding, earthquake, and wildfire (p.24), while oil spills are rarely investigated in the field of environmental planning.

2.4 Hydrological analysis

Water is the key component in environmental planning problems (Dunne, T., & Leopold, L. B., 1978). Planners and landscape architects use hydrological analysis to understand the movement of water over and under land surface, as well as the geomorphic, geochemical and biologic processes of water flow. Specifically, the estimate of the rate and amount of runoff as overflow is extremely important. The runoff is currently calculated using runoff models such as rational methods, Unit Hydrograph, SWAT, HSPF, HEC-HMS, etc., (Sitterson et al, 2017) which involve extensive data collection such as rainfall record, land use, slope and topography, soil properties, runoff coefficients table, etc. Resulting parameters like 10-year peak flow and annual runoff could help planners specify areas with intense hydrological processes to inform actions, goals, and developments for resilient communities.

In this paper, we investigate the environmental hazard and vulnerable environments around Fort Berthold Reservation in North Dakota by implementing USGS StreamStats, a web based analytical service. The goal is to present a form of analytical framework for environmental planning issues around pipeline oil spills.

3 METHODS

3.1 Watershed and flow network

This study uses Lake Sakakawea basin as the main study area for 4,940,539.18 Acres (6-digit HUC 101101) where the Fort Berthold Reservation is located at the south end downstream of the basin (Figure 1). Based on 2011 National Landcover data, the basin has roughly 36% of land as Herbaceous, 44% Cultivated Crops, 3.1% Development, 2.4% wetland, 1.8% deciduous forest, 1.3% shrub/scrub. 8.5% is Open Water where Lake Sakakawea is a 307,000-acre man-made reservoir created by Garrison Dam.

Since most oils are lighter than water, they flow on top of the water. Many oil spill incidents reach and damage lakes, rivers and wetlands through the surface flow network (Oil Program Center, 1999, p5-8). In January 2015, a pipeline burst contributed to a spill of over 3 million gallons of oil and wastewater into nearby Blacktail Creek and traveled 27 miles to reach the Missouri River (Cozzarelli et al, 2017). GIS data on flow network from NHDPlus Dataset by EPA was collected to the creeks, rivers, streams, canals, lakes, ponds etc. in the study area. This will help us locate the likely hazardous and vulnerable areas after oil spill incidents occur.

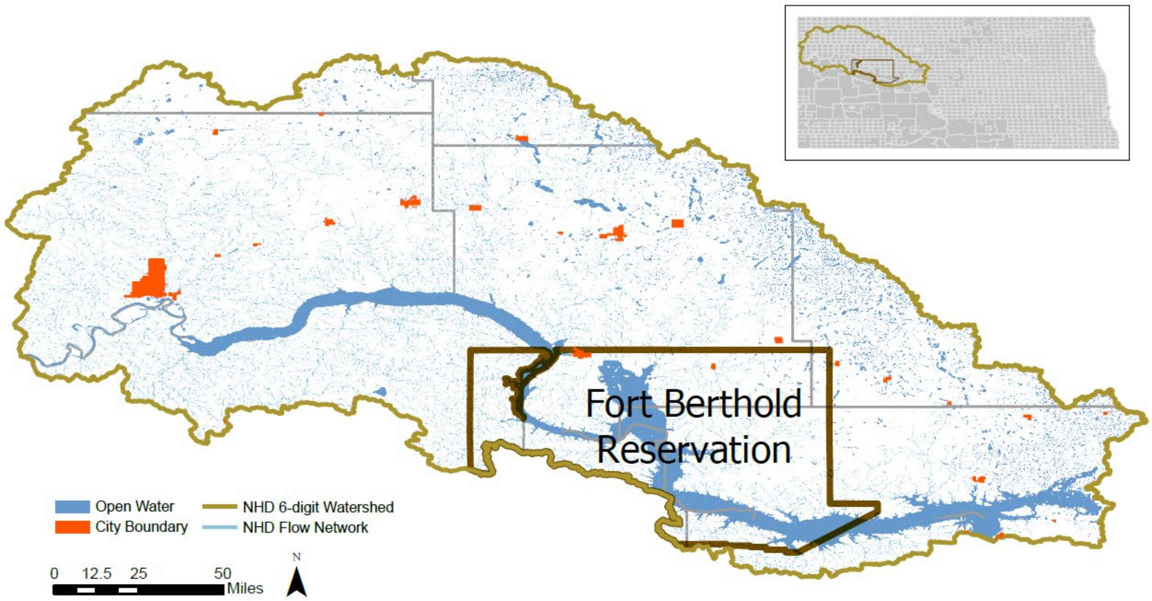

Figure 1. Study Watershed Basin and Fort Berthold Reservation

3.2 Hydrological analysis through StreamStats

Developed by the U.S. Geological Survey (USGS), StreamStats is a web application that provides hydrological modeling functionalities for water resources planning and management, and engineering purposes (Kernell G et al, 2008). This study will focus on two tasks using StreamStats:

3.2.1 Drainage basin delineation:

As the sample StreamStats report shows in Figure 2, the USGS StreamStats provides web services to delineate the drainage basin for a stream point (SP) of interest by integrating multiple datasets, such as the National Hydrography Dataset (NHD), the Watershed Boundary Dataset, and the 3D Elevation Program. In this study, we collected 101 points of interests where the streams enter the land boundary of Fort Berthold Reservation and then ran all the drainage basins for these points of interests. The resulting drainage basins will show all the areas where surface runoff flows into Fort Berthold Reservation to help identify the impacted watershed by potential Oil Pipeline Spills.

3.2.2 Streamflow modeling

The other key function by StreamStats is the automatic estimation of Streamflow Statistics for each drainage basin delineated (Figure 2). With large amounts of data from more than 25,000 Gaging Stations around the United States (USGS Gage Locations, 2018), the USGS has developed many regression equations that can be used to estimate various streamflow statistics for locations on ungauged streams throughout the nation. As an example, the equation for estimating the 100-year flood for ungauged sites of Northern Idaho is:

$Q100=5.39*DA*0.0874*(E/1000)-1.13*P*1.18$ (Berenbrock, 2002)

Where: Q100 is the peak flow that occurs, on average, once in 100 years (1-percent chance of occurrence in any year), in cubic feet per second; DA is the drainage area, in square miles; E is the mean basin elevation, in feet; and P is the mean annual precipitation, in inches.

StreamStats will automatically detect the correct equation for the drainage basin of interests and generate corresponding flow statistics. There are also API and batch services available for requests with multiple basins (only 200 requests are allowed each time). In this study, we developed a customized StreamStats requesting script using Python to fetch all the drainage basins and their corresponding 10-year peak flow rate in GeoJson format. All results will then be aggregated into a shapefile for further analysis.

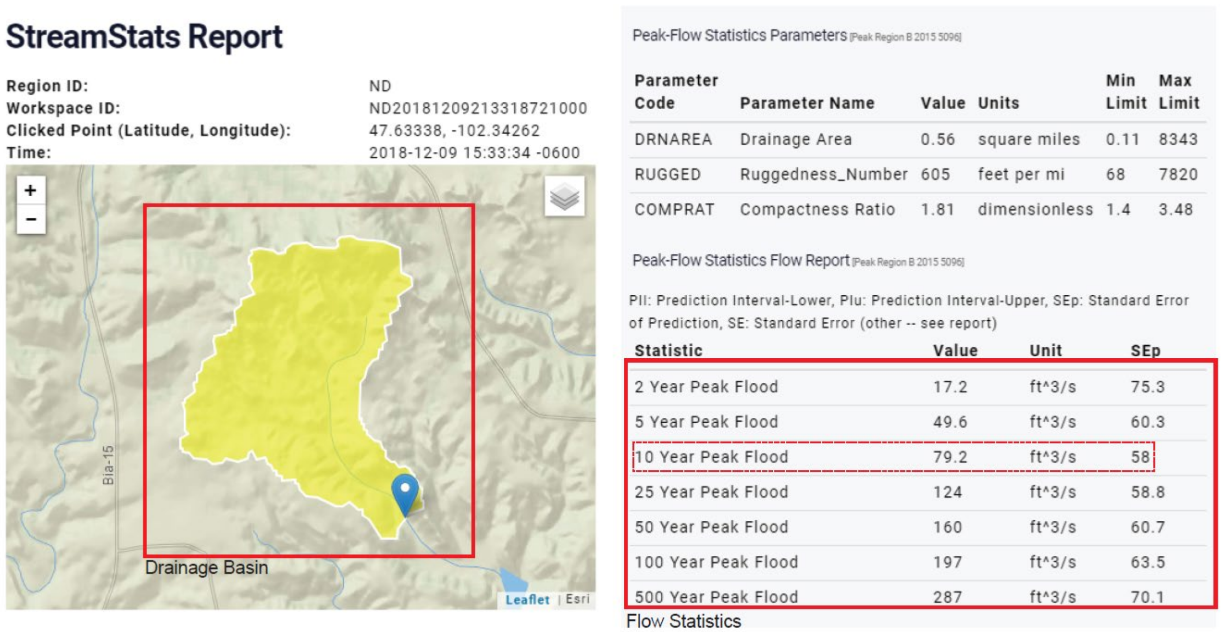

Figure 2. StreamStats Report

3.3 Hazard Indexing

After the hydrological analysis using StreamStats, we are able to estimate how much stormwater runoff will flow through each stream point (SP) on the reservation boundary at a 10-year event. We then estimated the overall runoff ratio of each cubic feet of rainfall at a 10-year event use (similar concept with Rational Method) the following equation:

$$R_{10\text{-}YEAR}=3600*12*Q_{10\text{-}YEAR}/(1.8*A) \qquad (1)$$

Where $R_{10\text{-}YEAR}$ is the runoff ratio of each cubic feet of rainfall at the 10-year event in the area; $Q_{10\text{-}YEAR}$ is the 10-year peak flow of the drainage basin calculated from StreamStats, in cubic ft per second; 1.8 is the 10-year rainfall intensity of the study area in inch per hour (Hershfield, D. M., 1961)); A is the area of the drainage basin, in square ft;

We then estimate the level of oil spill hazard by calculating a Hazard Index that using three assumptions:

1.Oil spills flow with the storm runoff, the $R_{10\text{-}YEAR}$ equals the runoff rate of each cubic feet of oil spill at the 10-year event in the area.

2.The probability (P) of oil spill per mile pipeline is equal and independent.

3.The estimated damage of a pipeline oil spill event is a constant X, there is no difference in terms of damage between multiple leaking spot simultaneously and one leaking spot.

Therefore, the Hazard Index (HI) for one drainage basin is calculated as:

$$HI=R_{10\text{-}YEAR}(1-(1-P)L)X \qquad (2)$$

We use an estimated ratio of P=0.1% from an analysis between 1982 and 1991 (Hovey, D. J., & Farmer, E. J, 1993); L is the total mileage of the pipeline in the drainage basin. 1-(1-P)L is the probability of at least one leakage of the total L mile pipeline in the drainage basin; the damage constant X=1000;

3.4 Vulnerability analysis

The Hazard Index (HI) can help compare and rank the damage level of the pipeline oil spill inflows at each stream point (SP). We then traced the downstream flow network for all stream points (SP) to identify the streams that will flow into reservation land. The Hazard Index will be aggregated to the downstream flow network to evaluate the vulnerability of the pipeline oil spill hazard for the reservation. Finally, we conducted an overlay analysis and descriptive statistics in ArcGIS for the ecosystem types being affected in the reservation.

4 RESULTS

Hydrological analysis started with the watershed delineation which provides a thorough understanding of drainage basins that flow into the reservation. As Figure 3 showed, all drainage basin delineations are generated from StreamStats and illustrated with 101 blue polygons in ArcGIS, with sizes ranging from 0.03 square miles to 221 square miles. 14 drainage basins (orange polygons) that have oil pipelines installed are identified as impacted basins in which most are from the west side of the reservation due to intense oil extracting and transporting activities.

Data gathered from StreamStats for Table 1 include all the basic characteristics of the impacted drainage basins such as mean slopes, length of longest flow path, average agriculture land percentage, mean basin elevation, total stream length, drainage area, average soil permeability and average percentage of impervious area, as well as the ten year peak flow rate, with the Basin ID in a clockwise order. The topography is relatively hilly with the median slope of 8.31 percent, especially at the west side of the reservation. Most impacted drainage basins are well-drained with a median average soil permeability of 1.57 inches per hour except the two at the north side where main agricultural lands are located. Overall, these basins consist of 573.61 miles of total streams, 363 square miles of drainage area, and a total of 6762.9 cubic feet per second 10-Year Peak Flow.

Table 1. Basic Characteristics of the Impacted Drainage Basins.

Basin Id	Mean Basin Slope from 10m DEM	Length of Longest Flow Path (mile)	Ag Land Percentage	Mean Basin Elevation	Stream Length Total (Mile)	Drainage Area (Square Mile)	Average Soil Permeability (Inches Per Hour)	Average Percentage of Impervious Landcover from NLCD 2011	10-Year Peak Flow Rate (Cubic Feet per Second)
1	11.21	22.99	14.29	2326.30	105.20	48.76	1.54	0.23	1085.43
2	8.26	16.43	32.78	2327.61	45.08	22.27	1.93	0.34	736.87
3	9.21	12.60	24.90	2301.87	63.31	24.34	1.92	0.45	1100.85
4	4.69	0.60	39.89	2306.45	0.26	0.13	0.94	0.68	20.70
5	6.47	2.28	17.75	2297.24	2.61	1.31	1.15	0.25	111.66
6	7.64	1.10	0.00	2317.39	0.73	0.38	0.97	0.00	53.20
7	8.37	0.86	0.00	2341.88	0.52	0.21	1.04	0.33	44.34
8	9.71	1.91	0.00	2331.75	3.73	1.00	1.18	0.10	147.19
9	17.79	4.71	0.82	2340.38	16.71	5.79	1.92	0.08	592.88
10	11.03	8.18	20.46	2349.33	21.47	8.84	1.96	0.35	561.69
11	9.59	3.51	26.37	2282.33	3.14	1.69	1.60	0.60	178.26
12	8.07	9.44	38.83	2286.95	30.22	13.69	1.46	0.37	490.11
13	5.21	12.52	45.14	2204.57	36.55	23.30	3.26	0.44	679.85
14	4.01	42.97	57.56	2121.63	244.07	211.44	3.64	0.26	959.88
Median	8.31	6.45	22.68	2311.92	19.09	7.32	1.57	0.33	525.90

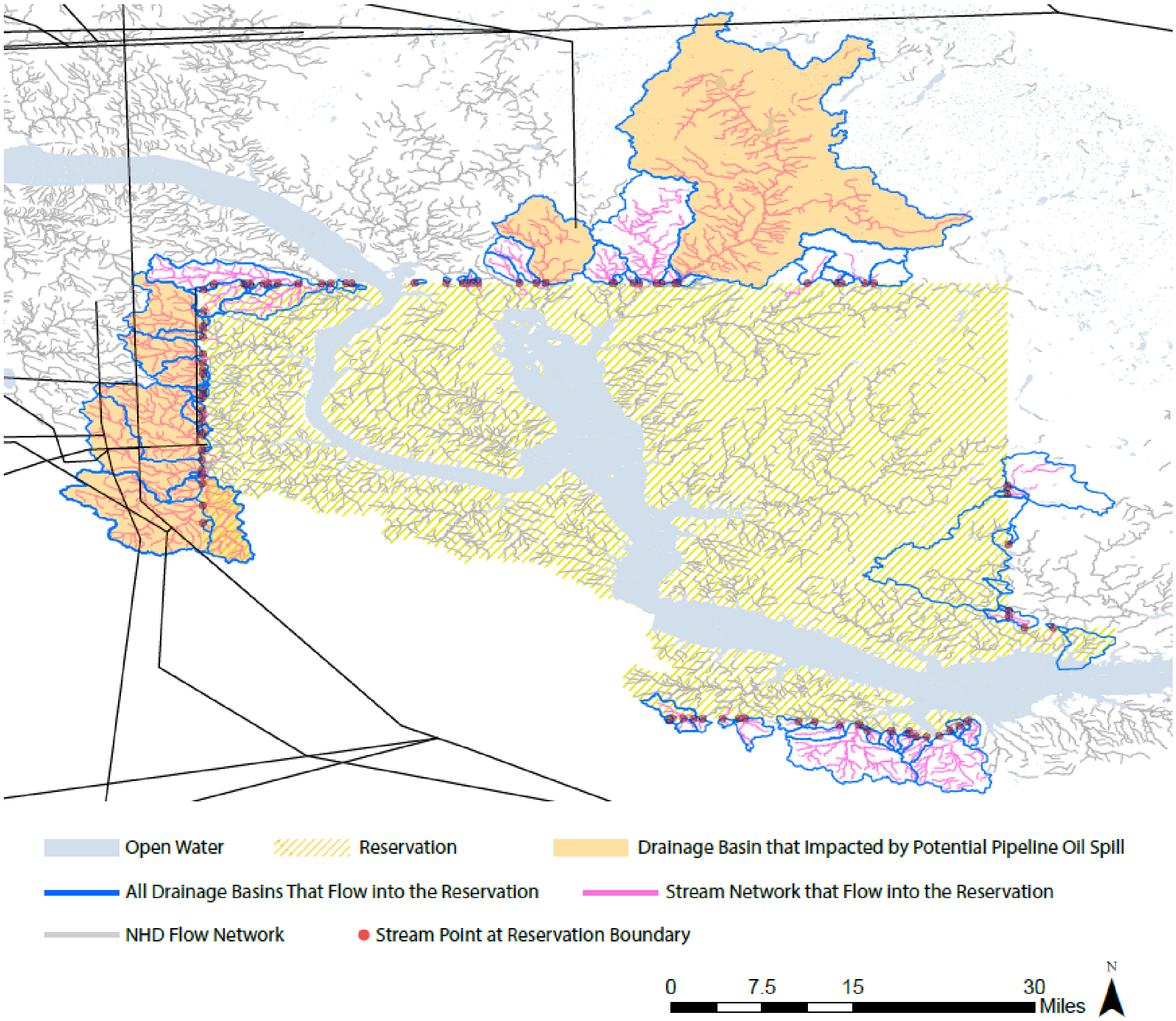

Figure 3. Drainage Basins in the Study Area

As the color-coded polygons in Figure 4 have shown, the Hazard Index provides quantifiable criteria to measure the expected impacts of each impacted drainage basin on the environmental safety of the reservation. The basins at the west side of the reservation have higher pipeline oil spill hazard than the two basins (ID 13&14) at the north. This is due to a densely located pipeline layout and higher 10-year runoff ratios (Table 2). Basin ID 1, 2 and 3 are the three most hazardous areas with multiple large-scale oil operation facilities between Mandaree, ND and Johnsons Corner, ND. Basin 4, 6, 7 and 8 are smaller basins with smaller Hazard Index but higher 10-year runoff ratios.

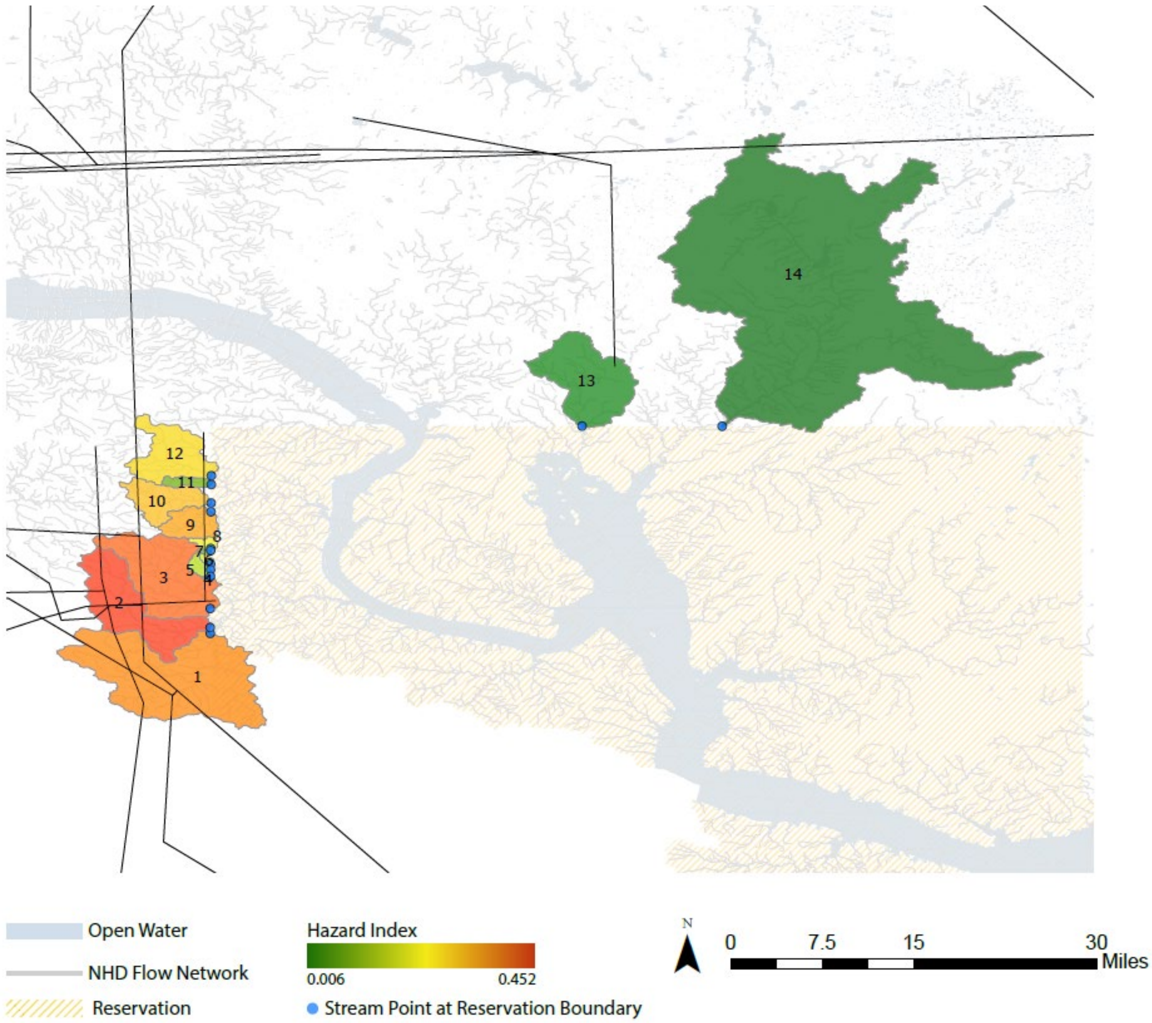

Figure 4. Hazard Index of Impacted Drainage Basins

Table 2. Flow Statistics and Hazard Index of the Impacted Drainage Basins.

Basin Id	Total Length of Pipelines in the Basin (mile)	10-Year Runoff Ratio	Hazard Index
1	23.181	0.019	0.439
2	16.627	0.028	0.470
3	11.669	0.039	0.452
4	0.265	0.136	0.036
5	0.949	0.073	0.070
6	0.700	0.122	0.085
7	0.367	0.183	0.067
8	0.767	0.127	0.097
9	2.517	0.088	0.222
10	3.276	0.055	0.179
11	0.671	0.091	0.061
12	4.488	0.031	0.138
13	0.727	0.025	0.018
14	1.653	0.004	0.006

Downstream tracings based on the direction information of the NHD flow network for the stream points (SP) at the reservation boundary of the impacted drainage basins. 71.56 miles of NHD flow networks were identified as vulnerable streams for ecological conservation and hazard management in the future. As Figure 5 shows, all the pipeline oil spill hazards will flow through four different creeks in which three are named as Bear Den Creek, Clarks Creek, and Shell Creek. We coded and aggregated each drainage basin Hazard Index value to all the corresponding streams based on their flow order. Therefore, the hierarchies of each stream segments can be evaluated as the color-coded polylines in Figure 5. Bear Den Creek, Clarks Creek, and their tributaries in the western part of the reservation are the most vulnerable areas, flowing into the Missouri River and Lake Sakakawea.

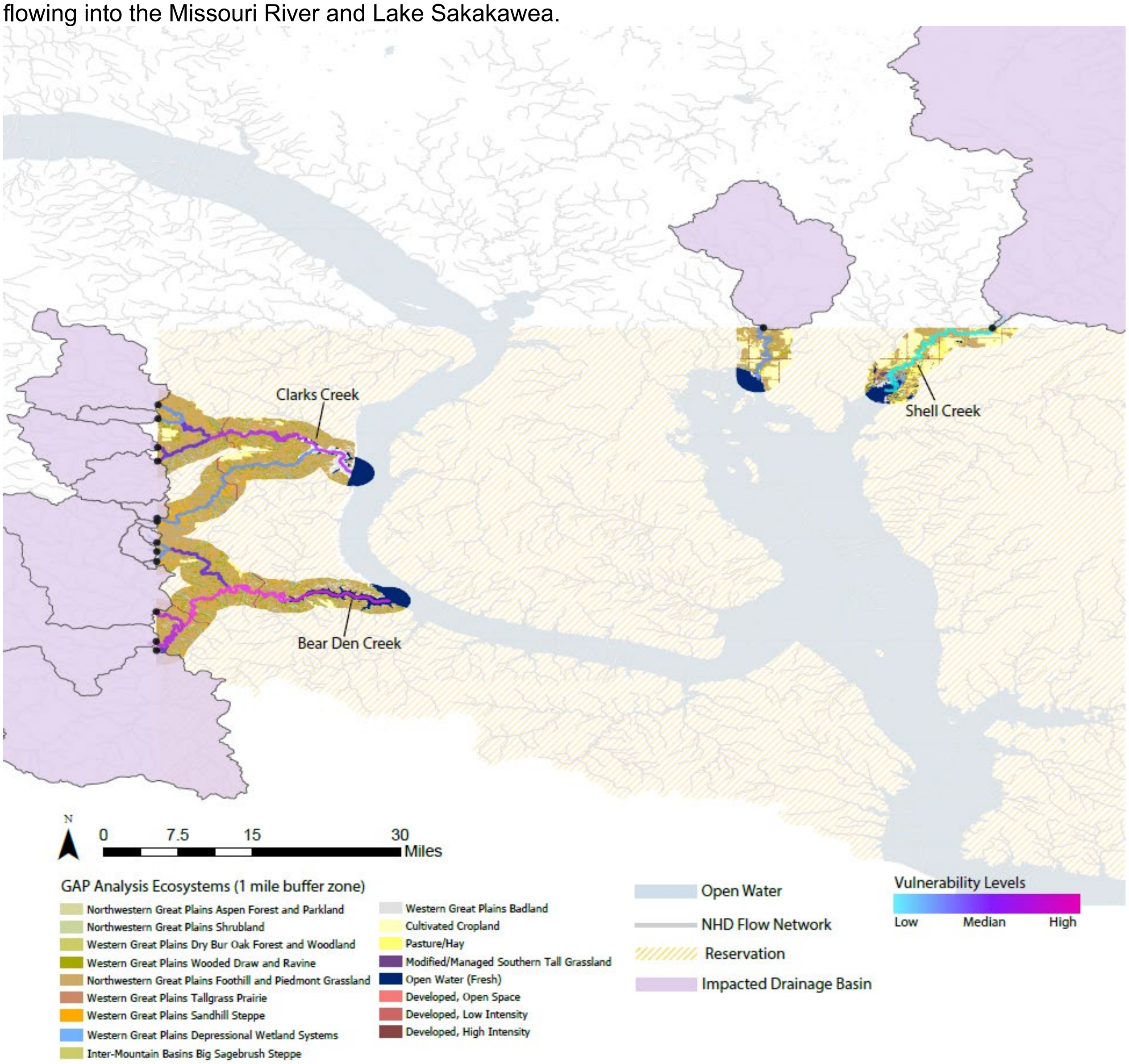

Figure 5. Vulnerable Streams

Finally, to give us a clear understanding on the impacted ecosystems typology, the Land Cover Data from the USGS National GAP Analysis Project was analyzed in the 1-mile buffer zone of the impacted streams (Figure 5). The Northwestern Great Plains Foothill and Piedmont Grassland are the most dominating ecosystems at 52.66% of the reservation, followed by Western Great Plains Wooded Draw and Ravine (10.86%), Cultivated Cropland (8.46%), and Open Water (7%). Table 3 lists all the ecosystems in percentage.

Table 3. Ecosystems in the Vulnerable Streams.

Ecosystems in GAP Analysis	Percentage
Northwestern Great Plains Shrubland	1.92
Western Great Plains Dry Bur Oak Forest and Woodland	2.22
Western Great Plains Wooded Draw and Ravine	10.86
Northwestern Great Plains Foothill and Piedmont Grassland	52.66
Western Great Plains Tallgrass Prairie	0.36
Western Great Plains Sandhill Steppe	5.12
Western Great Plains Depressional Wetland Systems	4.30
Inter-Mountain Basins Big Sagebrush Steppe	0.08
Western Great Plains Badland	1.46
Cultivated Cropland	8.46
Pasture/Hay	3.65
Modified/Managed Southern Tall Grassland	0.47
Open Water (Fresh)	7.00
Developed, Open Space	0.38
Developed, Low Intensity	0.14
Developed, High Intensity	0.91
Total	100

5 DISCUSSION

This study presents a method of identifying potential hazards for the Pipeline Oil Spills in North Dakota. By introducing NHDPlus flow network and USGS StreamStats, we were able to conduct Hydrological analysis (Figure 2) without sacrificing accuracy and reliability. Making requests from the StreamStats' large hydrology datasets, our drainage basin delineation and streamflow modeling tasks didn't have to include tedious data collection process such as land cover, precipitation, time of concentration, etc. We developed a customized Python Script to automate the estimation of peak flow runoff using StreamStats Web Service which utilizes regression techniques from large amounts of data from more than 25,000 Gauging Stations around the United States (USGS Gauge Locations, 2018). The processing time for the 101 points of interests cost approximately 2 hours. The results (Table 1 and 2) such as drainage area, soil permeability, and 10-year peak flow rate can help understand the hydrological characteristics of the region and inform environmental hazards of pipeline oil spills. With little modification, this hydrological analysis approach could also be used in many other regional planning objectives such as flood control, ecological restoration, and water resource management.

Additionally, we demonstrated the process of using StreamStats' 10-year peak flow results to estimate Pipeline Oil Spill Hazards for each drainage basin by developing a customized Hazard Index. Through this, it concluded that the drainage basins (Figure 4, Table 2) at the west side of the reservation between Mandaree, ND and Johnsons Corner, ND pose the most significant threats to Fort Berthold Reservation. This area has large amounts of oil industry operations present and should gain extra attention from land policymakers. Stricter hazard assessment and environmental monitoring actions are desperately needed before further water and soil contamination occurs. Ecological restoration investments should be made for lands currently suffering from sustaining environmental pollutions within the reservation.

Regarding the vulnerability analysis (Figure 5), we identified the vulnerable streams by down tracing the NHD flow network to assess the vulnerability level by aggregating the Hazard Index (HI) of corresponding upstream Stream Point (SP). Bear Den Creek and Clarks Creek are identified as high-risk areas in a pipeline oil spill event. Major impacted ecosystems are Northwestern Great Plains Foothill and Piedmont Grassland with large areas of mixed grass species such as Bluestem Grass and Needlegrass. The appearance of oil spill pollutants could harm the health of one or more species in the local food chain, which may lead to damage for food and water resources to human beings (Oil Program Center, 1999, p7). Tribal administration should prioritize these areas for conservation purpose, and if necessary, State and Federal agencies could also provide fiscal and policy incentives to facilitate projects that establish new natural communities for protecting potential threats.

This study focuses on pipelines as the major source of oil spill hazard. Other forms of oil spills from tankers, drilling rigs, wells, and refinery facilities are not considered. To gain a more holistic understanding of the environmental issues around Fort Berthold Reservation, more investigations are needed in the future.

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