Identifying Nonpoint Source Polluters in National Scale River Networks

Peiley Lau, Julia Longmate, and Solomon Hsiang

Existing policies regulating nonpoint source water pollution in California and beyond are difficult to enforce due to ineffective monitoring and gaps in available data. We propose a method that generates a more spatially and temporally resolved dataset to help identify sources of nitrogen and phosphorus pollution, with applications to the U.S. Mississippi River Basin and the country of New Zealand.

While California's agricultural industry is the country's leading producer of specialty crops, it is also the main source of water pollution in the state resulting from fertilizer and pesticide runoff. Despite the passage of the state-wide Porter-Cologne Water Quality Control Act (PCWQCA) in 1969, which regulates point and nonpoint source (NPS) pollution in surface water, groundwater, and wetlands, deteriorating water quality continues to afflict California. Discharge from known sources, such as toxic waste from factories or sludge from municipal treatment facilities, is known as point source pollution. In contrast, NPS pollution, including manure or excess fertilizer, originates from diffuse sources and is transported by precipitation into rivers or lakes.

In 2010, 8,000 miles of rivers and 300,000 acres of lakes across California were impaired from agricultural pollution and deemed unsafe for swimming or fishing. Furthermore, excess nitrate runoff contaminated drinking water, especially affecting communities in San Joaquin and Salinas Valleys.

The PCWQCA utilizes a permit system managed by the regional water boards. Each of the nine regional water boards (North Coast, San Francisco Bay, Central Coast, Los Angeles, Central Valley, Lahontan, Colorado River Basin, Santa Ana, and San Diego) sets its own water-quality control plan outlining regional water quality objectives and how the board will achieve these goals.

However, given the difficulty in tracing NPS pollution, California's water boards largely failed to implement an enforceable monitoring system for agricultural runoff that would successfully curb water pollution levels. In 2017, the Central Coast Regional Water Board deplored that "tens of millions of pounds of nitrate leach into groundwater in the Salinas Valley alone each year…[and] this presents a significant threat to human health as pollution gets substantially worse each year." A significant obstacle that regulators face is the self-reporting of on-farm nitrate applications. The sparse and infrequent water monitoring system renders it difficult to verify the veracity of the self-reports and identify the location of the heavy polluters.

The difficulties associated with monitoring NPS pollution and improving water quality are not unique to California's waterways. Our research focuses on two different regions facing water quality challenges. Our first case study is the U.S. Mississippi River Basin, where water pollution remains a salient environmental concern given the largely nonexistent federal oversight of agricultural runoff. In 2017, the anoxic Gulf of Mexico "Dead Zone" reached a record size of close to 9,000 square miles, surpassing the size of the state of New Jersey. The EPA attributes the Dead Zone to nutrient runoff from overapplication of fertilizer during the spring.

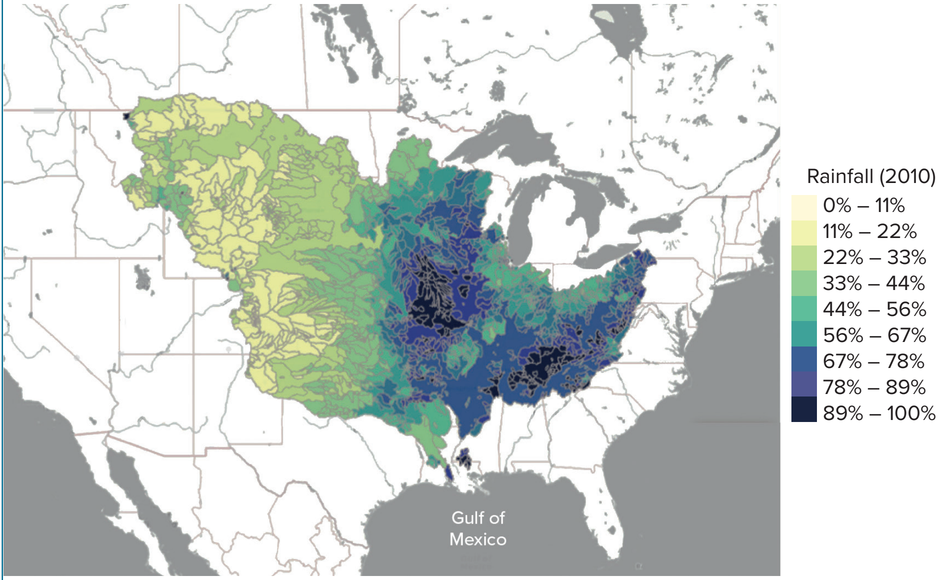
New Zealand, the other case study, is known for its robust and growing pastoral dairy and livestock farming industries. However, the country faces a water quality crisis associated with animal waste runoff. With over two-thirds of New Zealand's waterways deemed unsafe for swimming, addressing water pollution has become a top policy priority for New Zealanders, according to a 2018 public opinion poll.

A Spatial Model of Water Pollution

The challenge faced by all three of these regions is that without the ability to accurately monitor agricultural water pollution, policymakers cannot design policies targeting the pollution source and farmers might receive penalties for runoff originating from adjacent or upstream neighbors. In our work, we develop a spatial framework that combines water quality, flowrate, and elevation data to create localized annual estimates of nitrogen and phosphorus pollution quantities. Our approach can improve regulatory efficiency through better targeting of NPS polluters while minimizing the burden on farmers for reporting nitrate applications.

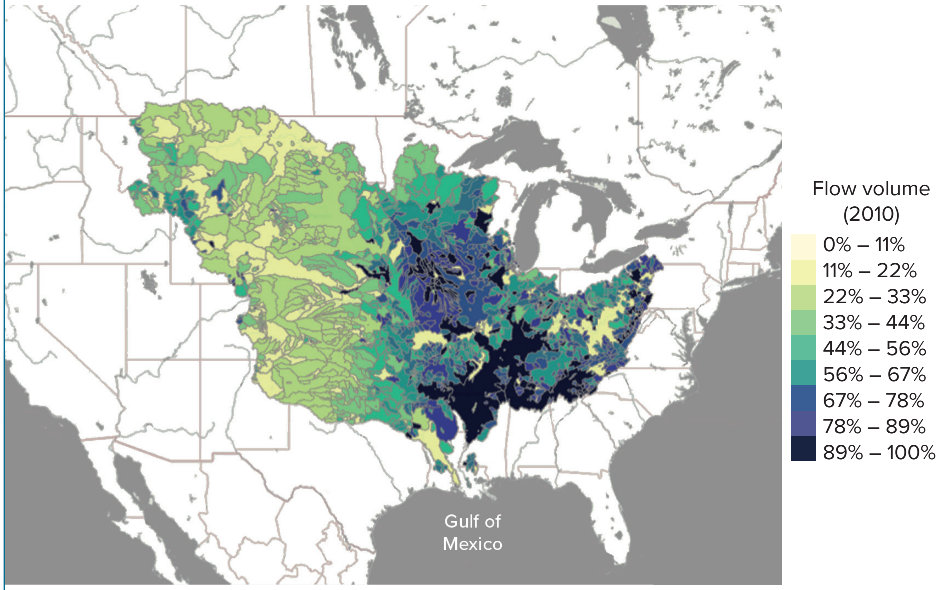
Tracing the source of NPS pollution is difficult because the pollution measured at a water monitoring site could come from any number of upstream regions. Our method localizes the pollution source by accounting for the regional topography and the location of monitoring sites along the river. Incorporating elevation data, and assuming that water flows downstream, lets us determine the path water would travel from any given point in that region. This allows us to predict for each unit of a pollutant that started from a point on the land, and if it were picked up by rainfall, the path it would take and where it would first

Figure 1. Rainfall Patterns in the U.S. Mississippi River Basin, 2010



Source: PRISM Climate Data, Oregon State University; map generated by authors

Figure 2. Flow Patterns in the U.S. Mississippi River Basin, 2010



Source: U.S.Geological Service; map generated by authors

enter the nearest waterway. Secondly, given that we know the location of existing water monitoring sites, we can determine which monitoring site first measures that pollutant as it flows past.

For example, imagine that there are two nearby monitoring sites, A and B, located along a river. Every unit of pollution that flows past upstream monitoring site A would also flow past downstream site B. However, not every unit of pollution that flows past site B necessarily flowed past the monitor at site A, since some of the pollution could have originated from land that was downstream of A. By taking the difference between the pollution measured at site A and B, our model can back out the amount of pollution that is attributable to the land area between the two monitoring sites. This is the intuition that drives our spatial approach.

We focus on nitrogen- and phosphorus-based chemical compounds that are commonly found in agricultural fertilizers and animal waste. Additionally, excessive levels of nitrogen and phosphorus in rivers and lakes can be detrimental to water quality because it leads to eutrophication through the promotion of excess algae growth, and can be harmful to human health.

The outcome of our research allows policymakers to look at maps that illustrate the quantity of NPS pollution that originated from a localized region in a particular year. This allows them to determine whether there are any pollution hotspots across space and what are the trends in various pollutants over time.

Ground Truthing our Spatial Approach

In order to double-check our method, we compare patterns of water flowing across space to the observed rainfall patterns in that year. In Figure 1, we visualize existing rainfall data and map the quantity of rainfall across the Mississippi River Basin subcatchments in 2010 colored by the decile of rainfall volume, where dark blue indicates higher amounts of rainfall and light yellow indicates a lower amount of rainfall in that catchment. Figure 1 shows that the western regions of the Mississippi River Basin were more arid, while the Midwest regions, especially around the Iowa-Missouri borders, and the Eastern South Central regions, received the highest quantities of rainfall in 2010.

In Figure 2, we take flowrate data (which measures the quantity of water flowing past a point along the river at a given moment in time) and run the data through our model. The interpretation of Figure 2 is that darker shaded subcatchments have higher levels of water originating from that region or, in other words, that region received higher levels of annual rainfall. We find that Figure 2 (which visualizes the model's results) recovers a similar spatial pattern of water volume as Figure 1 (which visualizes measured rainfall data), thus validating the model. While we cannot externally verify the pollutant loads estimated by our model, the ability to validate our approach using rainfall and water flow data helps to improve our confidence that our spatial approach recovers the movement of pollution across space.

Identifying Annual Pollutant Loads

We find that there is substantial heterogeneity in the amount of pollutant loads, even in neighboring catchments within the same state or regional council. In Figure 3, we visualize the quantity of total phosphorus (kg/km2/year) attributable to each of the subcatchments in New Zealand for which we had data for in 2015.

We find that most of the subcatchments in the top 20–30th percentile of total phosphorus loads are located in Waikato, Gisborne, and Taranki regional councils in the North Island. The subcatchments in the bottom 20–30th percentile for total phosphorus are located in Manawatu and Wellington regional councils. This is roughly consistent with the agricultural land use patterns in New Zealand. In 2019, over a third of New Zealand's dairy cattle reside in Waikato region, and another 14% of the country's dairy herd live in Taranaki. In contrast, Manawatu only grazes 5% and Wellington 4% of New Zealand's dairy cattle.

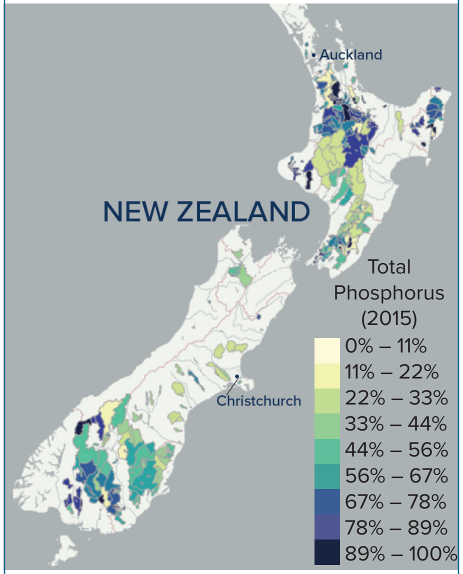
The overall pollution patterns across New Zealand reflect the land use in the area, where areas with higher populations of livestock tend to have higher levels of NPS pollution. Additionally, the model uncovers that even within a given region, there is a significant difference in the amount of pollution generated by nearby areas. This suggests that there are farms, perhaps due to their unique topography or farming practices, that are more susceptible to generating runoff. This result offers a valuable takeaway for California's agricultural industry since it demonstrates that it is possible to detect differences in agricultural runoff even at a small-scale level. This can simultaneously benefit both California's farmers and the health of the waterways, since regional water boards will have the ability to monitor local pollution and recognize farmers who already implement best practices and target areas that require more efforts to reduce runoff.

Conclusion

Our spatial methodology identifies sources of NPS pollution at a highly resolved spatial scale, allowing regional water boards to identify high polluting regions. Given that much of the existing water quality regulation around NPS pollution regulates water quality at an aggregate level, the maps that we have constructed allow policymakers to observe spatial heterogeneity in polluting behavior, even within the same district or region.

Additionally, the results of our work overcome the challenge of relying on self-reported fertilizer application, where farmers might underreport fertilizer quantities applied. Instead, given that our data use water-quality data measured in rivers, we can estimate the quantity of nitrogen- or phosphorus-based compounds attributable to a given subcatchment. Hopefully, this method will enable water agencies to improve their capacity to enforce and achieve their water quality objectives and improve the health of waterways for Californians and beyond.

Figure 3. Total Phosphorus Quantity Patterns in New Zealand, 2015



Source: Water quality and flow data from New Zealand regional councils; map generated by authors.

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For additional information, the authors recommend:

https://www.waterboards.ca.gov/water_issues/programs/nps/

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