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A Mixed-Methods Catchment Area Modelling Approach Using Free DEMs to Inform Environmental Surveillance in Kolkata, India and Accra, Ghana

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ABSTRACT

Environmental surveillance (ES) is an effective epidemiological tool that has successfully been used to monitor poliovirus circulation over the past three decades. ES has also emerged as a low-cost method to detect and estimate incidence of other diseases, such as typhoid fever and COVID-19. A limitation of ES in its current capacity stems from its reliance on sound working knowledge of the sewerage and sanitary system in the setting where it is being used. Without this knowledge, positive detection of a target pathogen in ES samples cannot be traced upstream to the likely source population. Additionally, selecting sites to collect samples for ES is speculative when this knowledge is absent, and samples may not capture the sub-population of interest and/or may capture overlapping sub-populations. Advances in digital elevation models (DEMs) captured through remote sensing, and their use in hydrologic modeling in ArcGIS, have expanded the potential for ES to be applied to areas where the sewage drainage systems are: 1) not well understood; 2) open to the environment; and/or 3) gravity-fed. Although a useful tool, historically this approach is less accurate when derived from free, open-access DEM datasets and applied to settings with hydraulic structures. These protocols, which were developed for a thesis project for a Master's in Public Health degree from Emory University, provide an innovative mixed-methods mapping approach that addresses the current limitations of ES and the use of catchment area delineation for ES using free, open-access data. DEM Reconditioning, a tool in ArcHydro, was applied to improve the accuracy of free DEMs. This methodology was applied to two case studies in unique settings where ES research is underway. The first case study is in Kolkata, India, where ES samples were collected and tested for *Salmonella* (*S.*) Typhi and *S.* Paratyphi A to supplement clinical surveillance of typhoid and paratyphoid fever. A hybrid model was developed that integrates information about hydraulic structures and hydrologic processes that comprise the sewage drainage system in Kolkata. This model was used to estimate the geographic area and population size represented by sewage samples collected from thirteen pumping stations. In the second case study, a catchment area model was developed to identify optimal sampling locations for ES of COVID-19 in Accra, Ghana. This thesis confirmed that a mixed-methods approach can unify free, open-access information and be used to map sewage drainage systems in settings where ES has historically been limited. The Kolkata model demonstrated how this methodology can be used retroactively to inform interpretation of results from ES samples. The Accra model demonstrated that this process can be used proactively to identify strategic sampling points that capture sub-populations of interest, prevent catchment population overlap, and maximize coverage.

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52713

GUIDELINES

These protocols, which were developed for a thesis project for a Master's in Public Health degree from Emory University, provide an innovative mixed-methods mapping approach that addresses the current limitations of environmental surveillance (ES) and the use of catchment area delineation for ES using free, open-access data. Please read the section under "Before start" and the Abstract before working through the steps. The Materials section also provides links to resources you may find helpful, as well as sources that were used to create this methodology.

MATERIALS TEXT

Software:

- ArcGIS Pro: To install ArcGIS Pro, visit the ESRI website (https://www.esri.com/en-us/home) to learn about various packages and pricing details. From this website, ArcGIS Pro can be downloaded and installed for use depending on the person's or institution's preference.
- Arc Hydro Extension: ESRI provides several versions of Arc Hydro to match different ArcGIS versions. To download the Arc Hydro extension, visit http://downloads.esri.com/archydro/archydro/. For this project, the ArcGIS Pro extension was downloaded and installed.
- QGIS (free and open source GIS): https://www.qgis.org/en/site/
- QuickOSM plugin in QGIS
- QuickMapServices plugin in QGIS

- OpenStreetMap (optional): https://www.openstreetmap.org/#map=4/38.01/-95.84
- Overpass Turbo (optional): http://overpass-turbo.eu/

Materials:
An exhaustive online search was performed to gain knowledge about Kolkata's complex sanitation landscape. The sources of information included textbooks, historical city planning reports, records of upgrades and projects, scientific literature, government websites, surveyed performed at pumping stations, and news and blog articles:

- World Bank. *India - Vulnerability of Kolkata Metropolitan Area to Increased Precipitation in a Changing Climate*. Washington D.C.; 2011. http://documents.worldbank.org/curated/en/834561468041134833/India-Vulnerability-of-Kolkata-metropolitan-area-to-increased-precipitation-in-a-changing-climate.
- Calcutta Metropolitan Planning Organization. Master Plan for Water Supply, Sewerage, and Drainage Calcutta Metropolitan District 1966-2001.
- Basu N, Dey A, Ghosh D. Kolkata's brick sewer renewal: History, challenges and benefits. *ICE Proc Civ Eng*. 2013;166:74-81. doi:10.1680/cien.12.00016
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- Government of West Bengal. Irrigation & Waterways Department. https://wbiwd.gov.in/index.php/applications/kolkata_drainage. Accessed March 21, 2021.
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- Mukherjee J. *Blue Infrastructures : Natural History, Political Ecology and Urban Development in Kolkata*. Vol 1st ed. 20. Singapore: Springer; 2020. https://login.proxy.library.emory.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=nlebk&AN=2486075&site=ehost-live&scope=site

Methodology Acknowledgement:
The following resources and tutorials were referenced to guide development of the protocols:
- ESRI. *Arc Hydro Tools - Tutorial*.; 2011. http://downloads.esri.com/archydro/ArcHydro/Tutorial/Doc/Arc Hydro Tools 2.0 - Tutorial.pdf.
- Li Z. Watershed modeling using arc hydro based on DEMs: a case study in Jackpine watershed. *Environ Syst Res*. 2014;3(1):11. doi:10.1186/2193-2697-3-11
- Sharma S, Jain A, Singh AK. *Watershed and Stream Network Delineation Using ArcHydro*.; 2015. https://www.researchgate.net/publication/286530037_Watershed_and_Stream_Network_Delineation_Using_ArcHydro. Accessed March 14, 2021.
- Tarboton DG, Bras RL, Rodriguez-Iturbe I. On the extraction of channel networks from digital elevation data. *Hydrol Process*. 1991;5(1):81-100. doi:10.1002/hyp.3360050107

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BEFORE STARTING

Installation of ArcGIS Pro, QGIS, and Arc Hydro Extension (or other mapping software)

Oftentimes, a university or organization has purchased an ArcGIS license, and this subscription can be extended to a user at the institution. ArcMap can also be used to perform watershed delineation and the other mapping tasks discussed in this methodology. For those who do not have access to an ArcGIS license through their employer or educational institution, however, installation is rather costly. It is possible to perform this methodology using QGIS, a free, open source GIS software, and this software should be explored to make this methodology more accessible to users around the world. For this research project, Emory University's ArcGIS Pro license was extended and installed onto a personal computer.

To install ArcGIS Pro, visit the ESRI website (https://www.esri.com/en-us/home) to learn about various packages and pricing details. From this website, ArcGIS Pro can be downloaded and installed for use depending on the person's or institution's preference.

To download QGIS (free and open source GIS software), visit https://www.qgis.org/en/site/forusers/download.html and download the appropriate version for your platform.

ESRI provides several versions of Arc Hydro to match different ArcGIS versions. To download the Arc Hydro extension, visit http://downloads.esri.com/archydro/archydro/. For this project, the ArcGIS Pro extension was downloaded and installed.

Case Study #1: Kolkata, India

1 Investigative Research

Intensive research was performed to increase understanding about Kolkata's complex sanitation landscape. This research was necessary to conduct for Kolkata due to the drainage system's vastness, complexity, and history of patchwork upgrades.

1.1 The following types of information were utilized for the investigative research: textbooks, historical city planning reports, public records of upgrades and projects, scientific literature, government websites, surveys performed at pumping stations, and news articles. If possible, local experts on the sanitation infrastructure should be consulted. Such experts may have irreplaceable knowledge and resources that can significantly improve the accuracy of the model.

1.2 A consistent finding across the sources of information was that the general

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direction of water drainage was south-eastward across Kolkata.

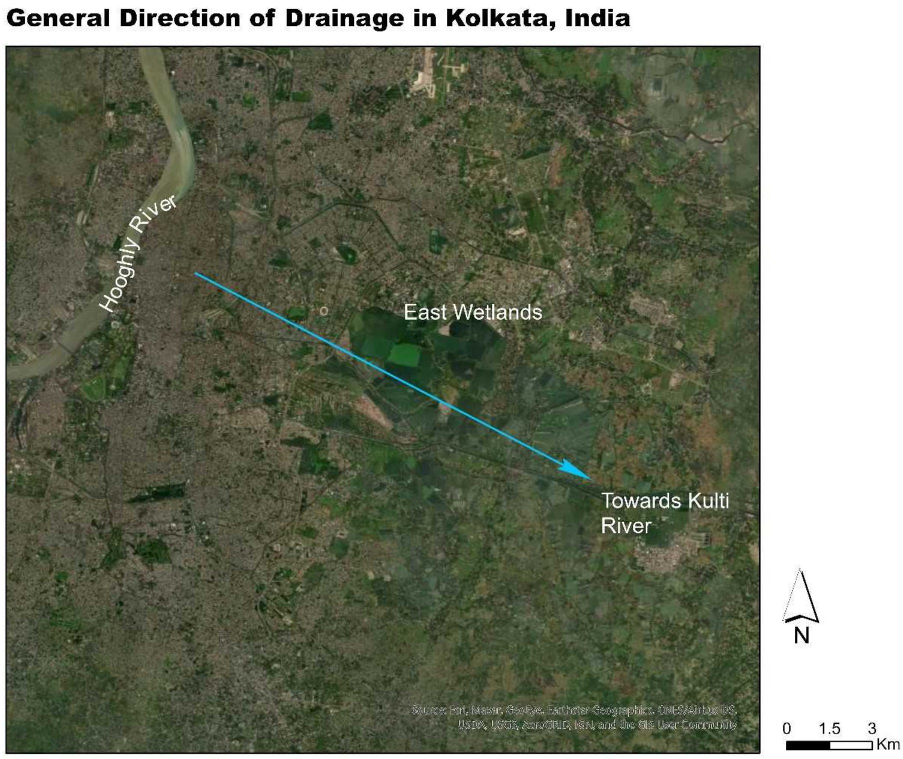

Figure 1. General direction of drainage is in southeasterly direction, from the Hooghly River through the East Kolkata Wetlands towards the Kulti River and, eventually, into the Bay of Bengal.

1.3 Diagrams of underground sewer and storm water lines for three drainage systems in Kolkata were found online, and these were integrated into the model to create a hybrid hydraulic - hydrologic model. These diagrams do not cover the entire Kolkata Municipal Corporation, but provide highly valuable information about how sewage and storm water are transported in some parts of the city.

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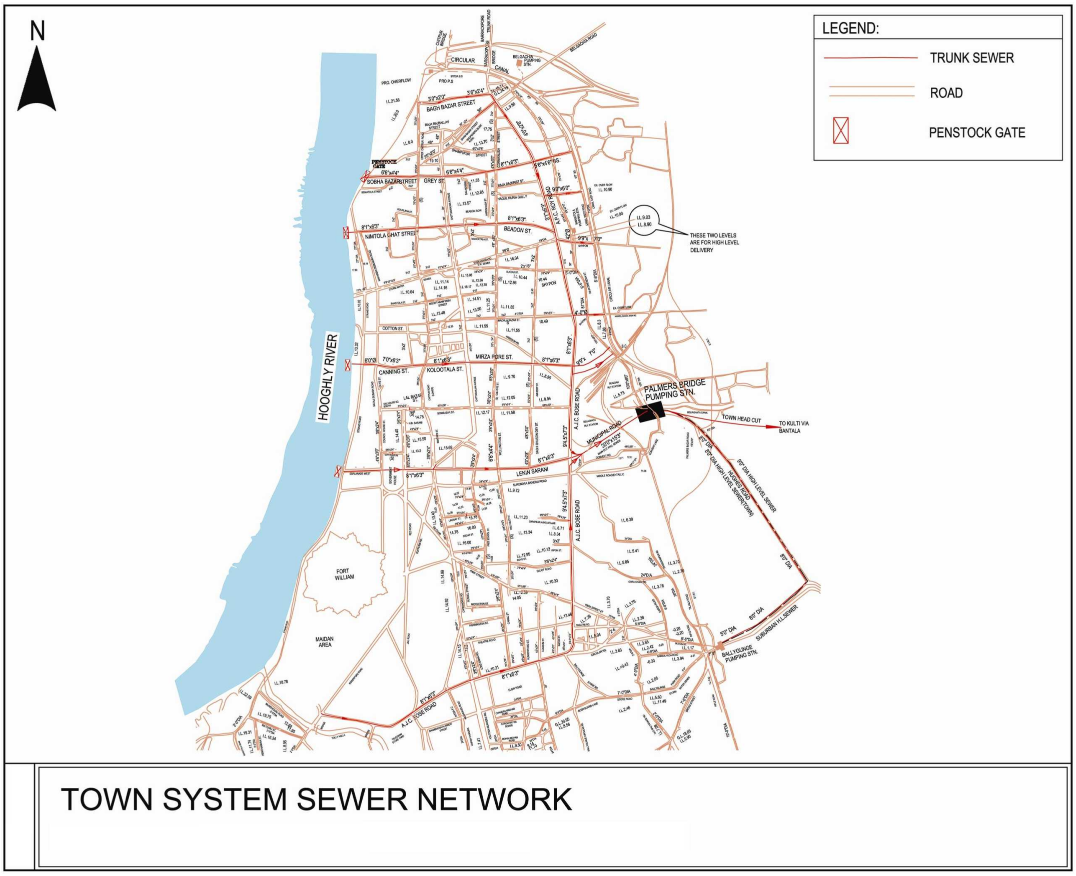

Figure 2. Town System sewer network diagram.

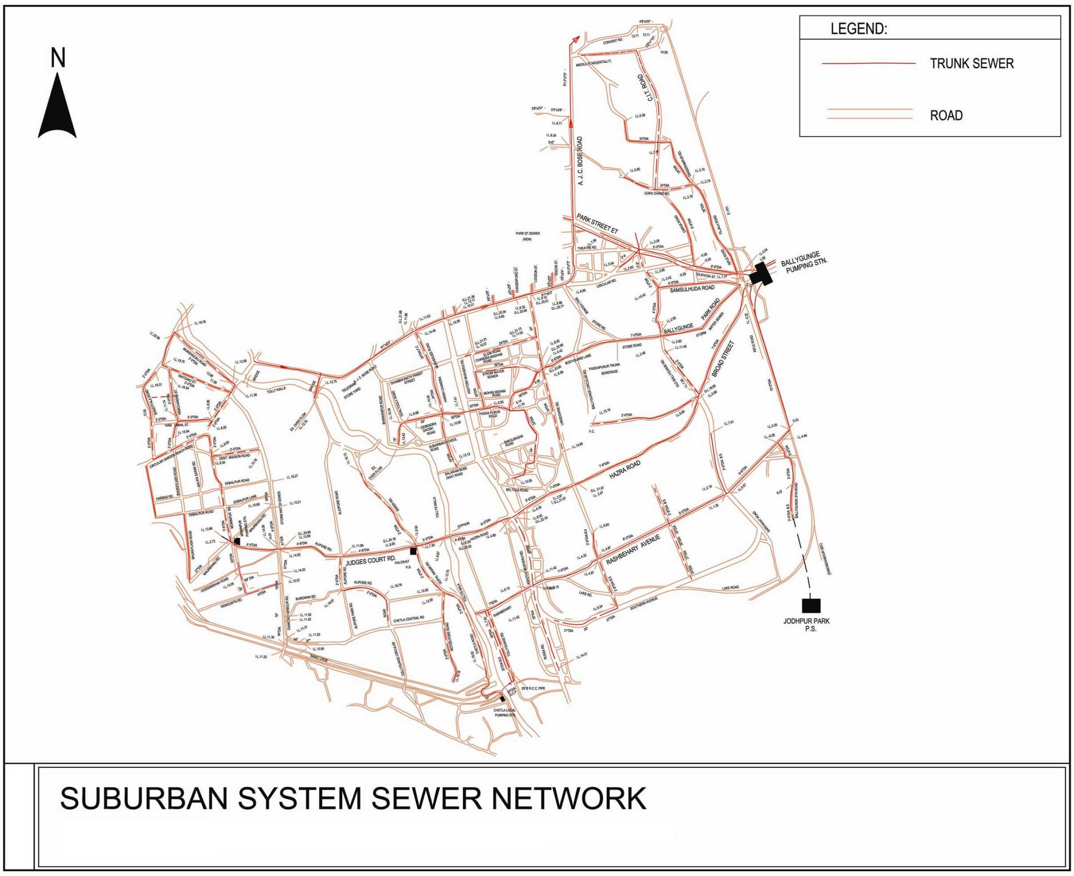

Figure 3. Suburban System sewer network diagram.

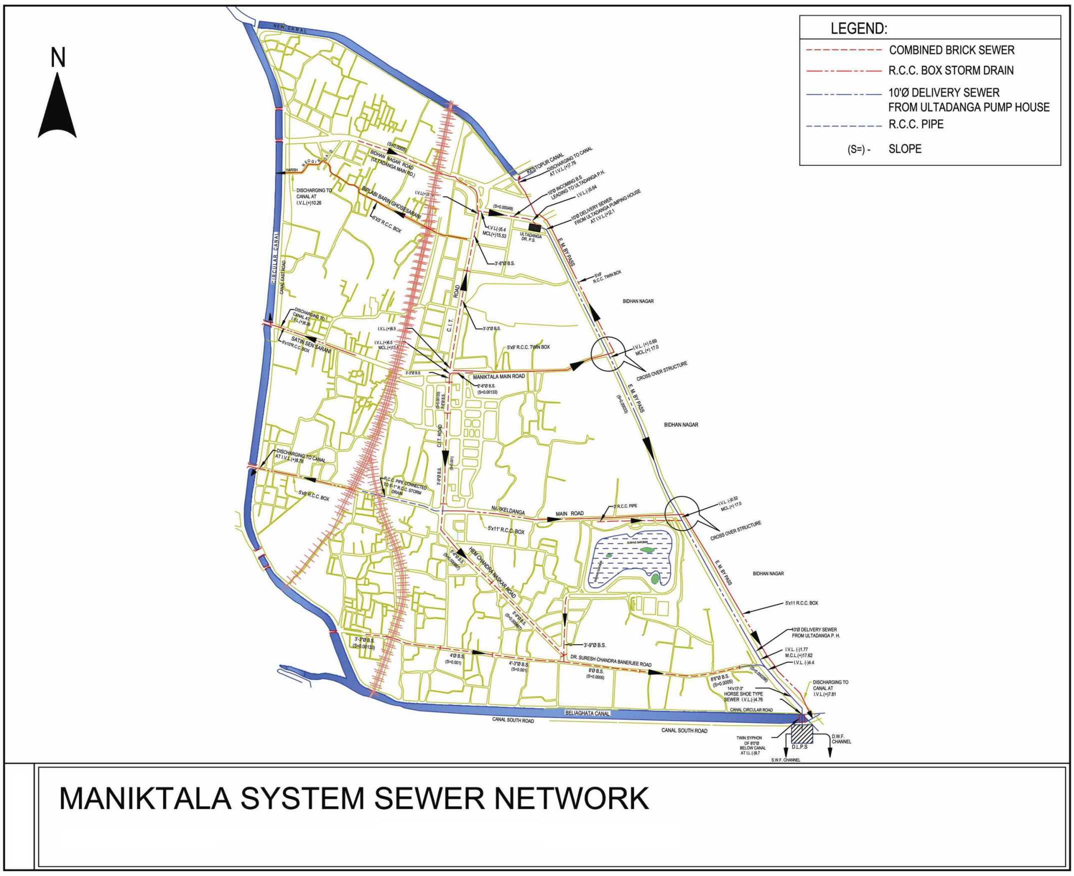

Figure 4. Maniktala System sewer network diagram.

2 Downloading DEMs from USGS EarthExplorer

A Digital Elevation Model (DEM) is a raster of elevation data for a specific region. This is the raw ingredient from which the hydrologic model is built.

2.1 Free DEMs were downloaded from the website https://earthexplorer.usgs.gov/. The user must create an account before data can be downloaded.

2.2 A polygon was drawn around the area of interest that encompassed Kolkata (Figure 5).

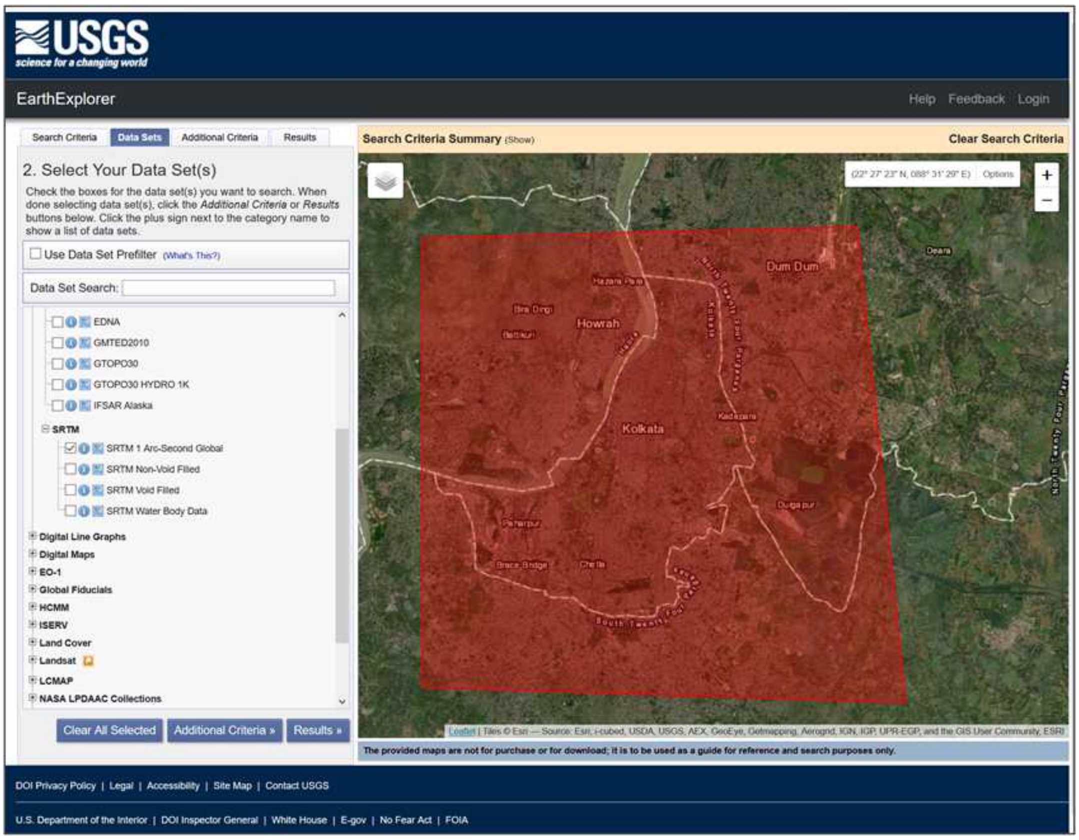

Figure 5. Polygon drawn around Kolkata to locate DEMs in this region to download from USGS EarthExplorer.

2.3 The "Data Sets" tab was selected, then the following selections were made from the drop-down list:

- Digital Elevation
- SRTM
- SRTM 1 Arc-Second Global

2.4 The "Results" tab was clicked, and the DEM was then downloaded as a GeoTIFF file.

3 Extracting Waterways from OpenStreetMap

Freely available DEMs have a resolution quality of 30 meters (30-m by 30-m pixels). This resolution is oftentimes too low for ArcGIS to detect all of the waterways, particularly in densely populated areas with flat terrain. To improve the quality of the DEM, waterways can be "burned" into the DEM through a process called DEM Reconditioning. This step lowers the elevation values of the DEM where a waterway is located (this process will be described in later steps). The waterways features were extracted from OpenStreetMap (OSM) using the QuickOSM plugin in QGIS.

3.1 To download the QuickOSM plugin in QGIS, select the "Plugins" tab at the top of the window and then "Manage and Install Plugins". In the search bar, type in "QuickOSM" and select "Install Plugin".

> The QuickOSM plugin in QGIS was used rather than downloading layers from OpenStreetMap, which requires running a query in OverpassTurbo, exporting the files, and uploading them in a mapping software. The QuickOSM plugin conveniently creates the query and pulls up the resulting layers in QGIS, allowing for easy viewing and editing of the features.

3.2 To download the QuickMapServices plugin in QGIS, select the "Plugins" tab at the top of the window and then "Manage and Install Plugins". In the search bar, type in "QuickMapServices" and select "Install Plugin".

> This plugin allows you to set the basemap from an extensive list of options. A Google Terrain basemap was set as the background for this project.

3.3 Using the Google Terrain basemap, the area of interest (i.e., the city of Kolkata and surrounding environment) was zoomed in to the extent in which waterway features were desired to be extracted.

> This will create the spatial extent in which the QuickOSM plugin will mine for waterway features. Note that the larger the area, the longer it was will take to execute the query.

3.4 In the QuickOSM plugin in QGIS, the “Quick query” option was selected, and the following fields were selected (Figure 6):

- Key: waterway
- Layer Extent: Google Maps

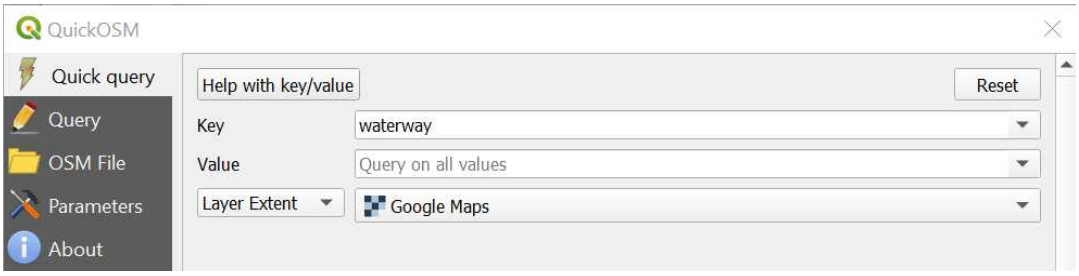

Figure 6. Inputs into “Quick query” within the QuickOSM plugin in QGIS. This query extracts features tagged as “waterway” from the OSM database within the Google Maps spatial extent.

3.5 Under the “OSM File” tab, the points option was deselected (points are not necessary for this task, and it helps the query run more quickly). Next, “Show query” was selected, which reveals the code shown in Figure 7.

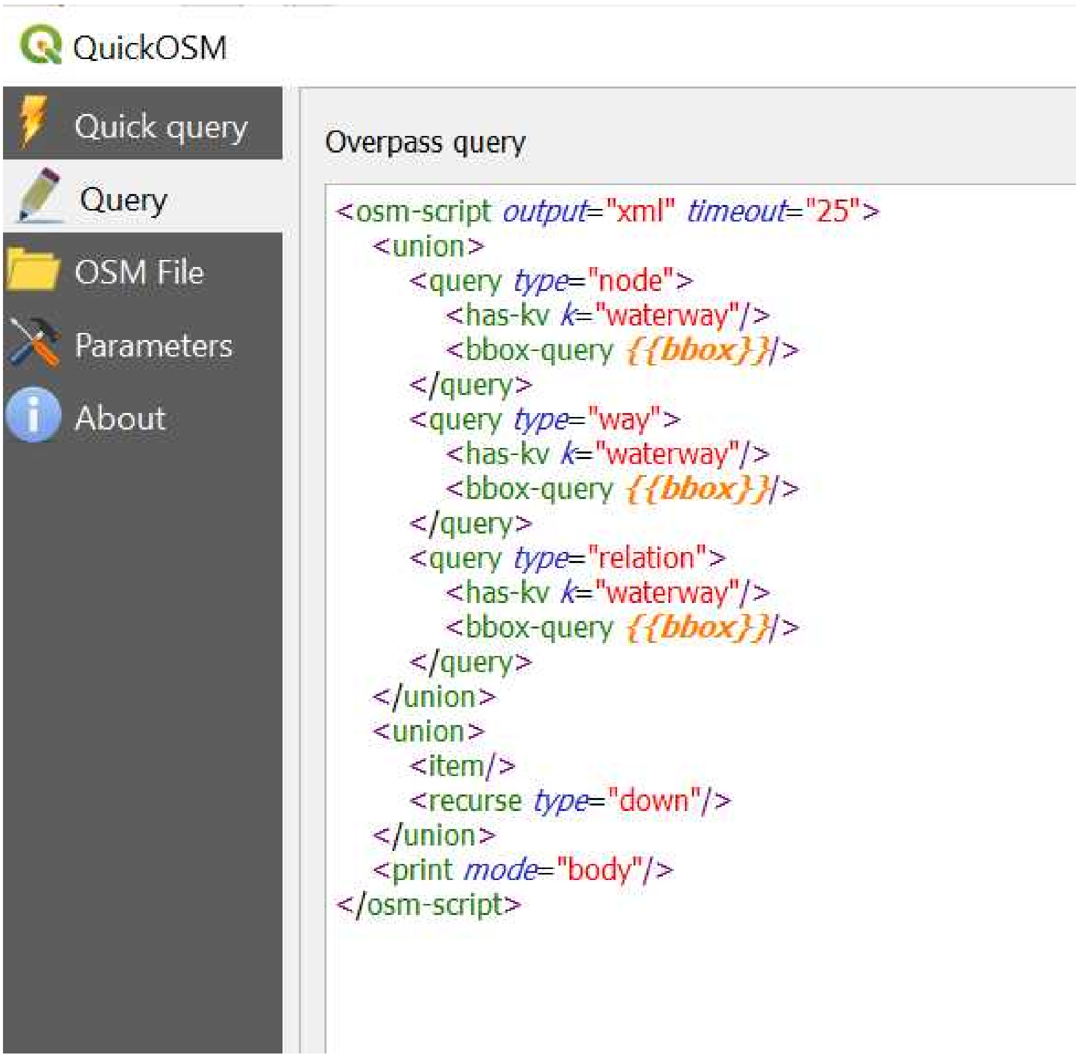

Figure 7. The query that is run through the Overpass Turbo data mining tool for OSM.

3.6 The query was executed by selecting “Run query”. The output from this operation is shown in Figure 8.

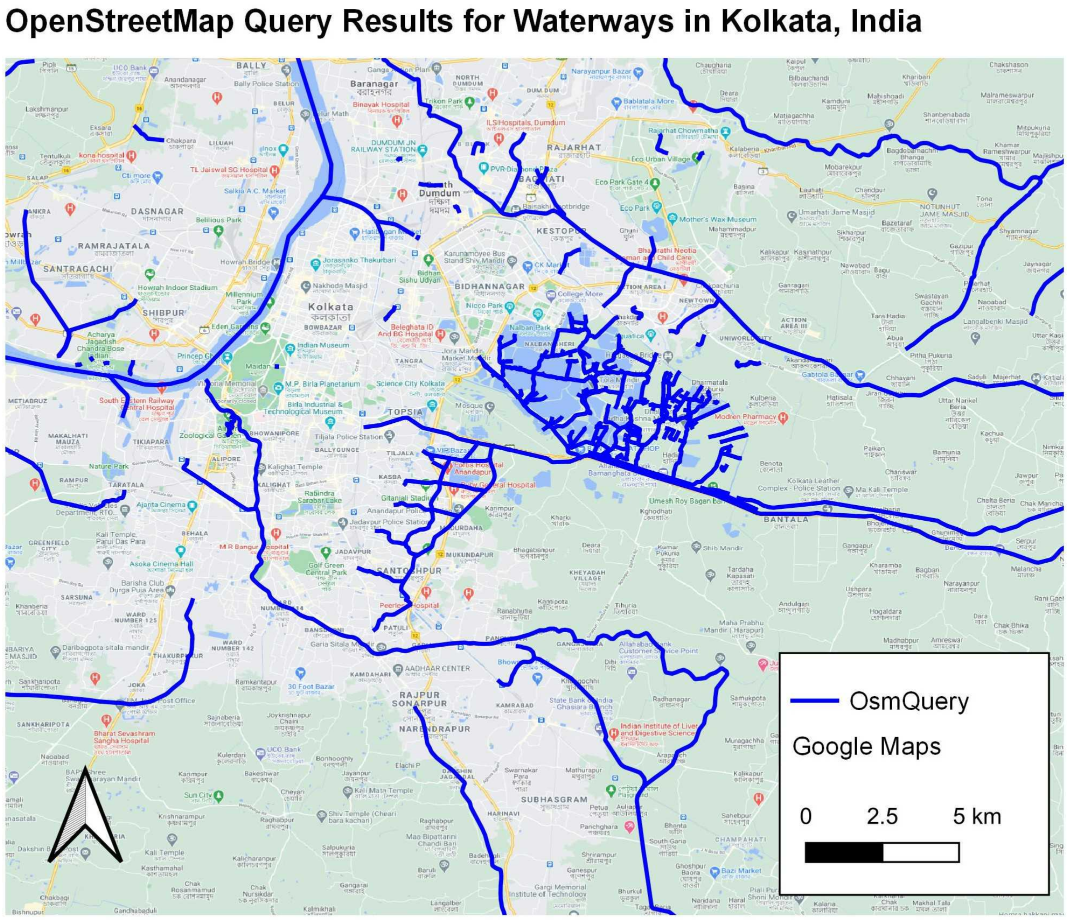

Figure 8. Results from the waterways query using the QuickOSM plugin in QGIS.

> QuickOSM files are automatically saved as scratch layers (i.e., temporary layers that will disappear once you close out of the project). To make a layer permanent, right click the layer and select "Make Permanent".

3.7 Several waterways were missing or incomplete, which was evident from comparing the results from QuickOSM with the waterways visible in Google Terrain. This was corrected using the edit tools in QGIS by manually adding missing waterways, extending incomplete lines, and deleting inaccurate lines using the Google Terrain basemap as a guide (see Figures 9 - 10).

This process can be relatively time-consuming (depending on the geographic extent and quality of the query results); however, it is made significantly easier by the outputs of the OSM query.

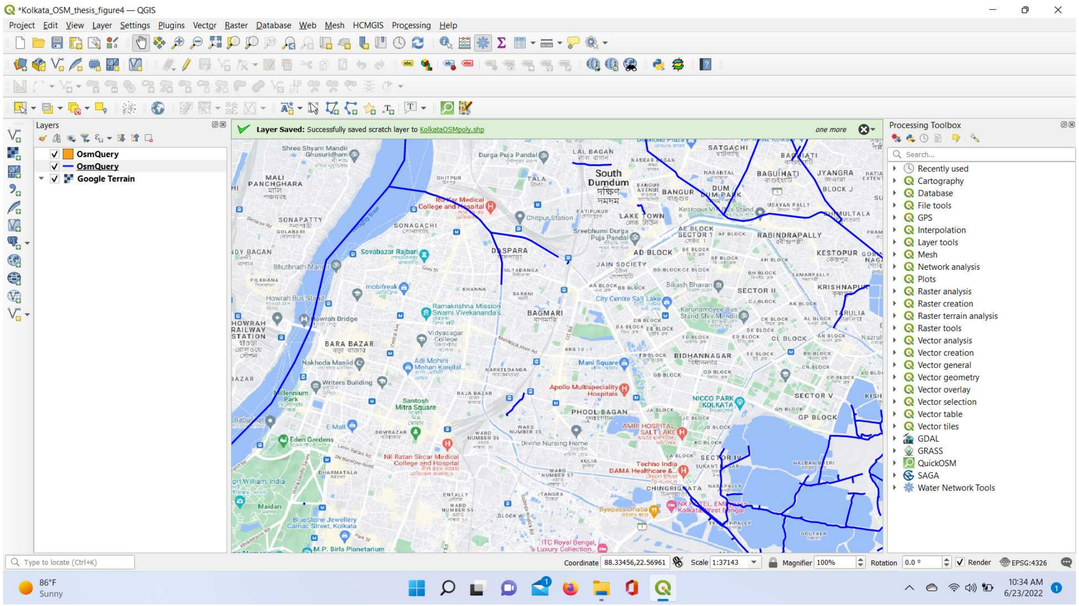

Figure 9. Results from QuickOSM plugin in QGIS. There are several waterways that are missing or incomplete (i.e., there are no dark blue lines where there are clearly waterways shown in Google Maps).

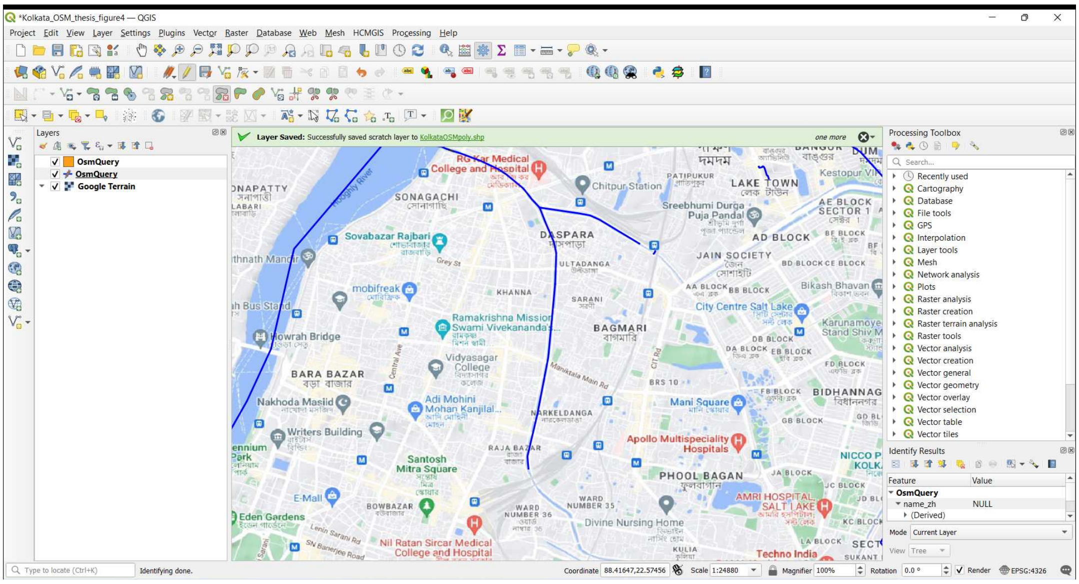

Figure 10. Example of a waterways feature that was extended and a feature that was deleted to match waterways as they appear in Google Terrain.

3.8 Waterways were then categorized into three groups based on their widths, which were measured using the measurement tool in Google Maps (Figure 11). The classifications were defined as such: small (width </= 12m); medium (12m < width </= 50m); large (> 50m).

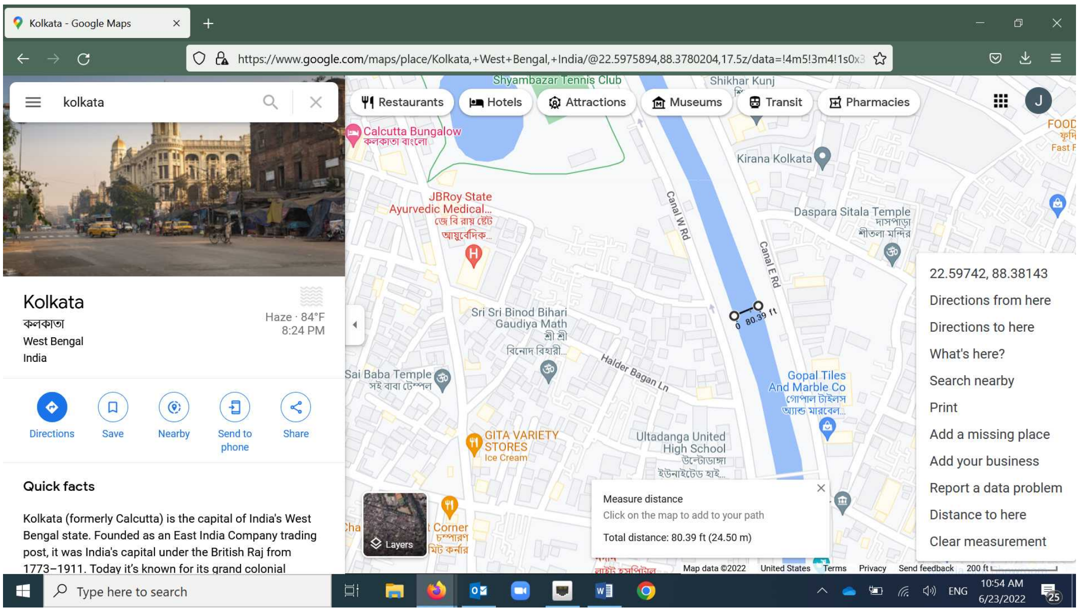

Figure 11. Using the measurement tool in Google Maps, widths of waterways were measured to classify waterways as small (width </= 12m), medium (12m < width </= 50m), or large (> 50m).

3.9 Separate features were created for small, medium, and large waterways. This was performed by selecting waterway features one category at a time, exporting the selected features, and naming them accordingly. For example, to create the small waterways feature, all small waterways were selected by holding the shift key while clicking the features classified as small. The layer was then right-clicked, "Export" was selected, then "Save Selected Features As.." was selected. The new shapefile was named "SmallWaterways" and exported to the project folder.

4 Import DEM in ArcGIS Pro

From this this step onward, ArcGIS Pro was used.

4.1 The DEM downloaded from USGS EarthExplorer was imported into the mapping software (ArcGIS Pro).

4.2 Using the "Project Raster" tool, the DEM was projected to CRS “WGS 1984 / UTM Zone 45N”. This CRS was selected due to Kolkata’s location between 84°E and

90°E in the northern hemisphere above 84°N.

5 DEM Reconditioning

The DEM Reconditioning tool will be used to burn waterways into the DEM. This step lowers the elevation values of the DEM where waterways are located. The waterways extracted with the QuickOSM plugin will be used for this process. These steps were performed iteratively (i.e., the output from the previous execution is used as the input in the next execution) to burn in waterways according to their size category to create a more realistic reconditioned DEM.

5.1 The separate waterway shapefiles from Step 3.9 were converted into raster format using the “Feature to Raster” tool and projected to the Coordinate Reference System (CRS) “WGS 1984 / UTM Zone 45N”.

5.2 Using the "DEM Reconditioning" tool within the Arc Hydro toolkit, DEM reconditioning was first performed with the small waterways raster. The following values were entered into the fields:

- Number of cells for stream buffer: 1
- Smooth drop in Z units: 1
- Sharp drop in Z unis: 10

5.3 Using the output from Step 5.1 as the input in the next DEM Reconditioning run, the medium waterways raster was burned in. The following values were entered into the field:

- Number of cells for stream buffer: 2
- Smooth drop in Z units: 5
- Sharp drop in Z unis: 10

5.4 Using the output from Step 5.2 as the input in the last DEM Reconditioning run, the large waterways raster was burned in. The following values were entered into the field:

- Number of cells for stream buffer: 5
- Smooth drop in Z units: 10
- Sharp drop in Z unis: 10

5.5 The results from the DEM Reconditioning process are shown in Figure 12.

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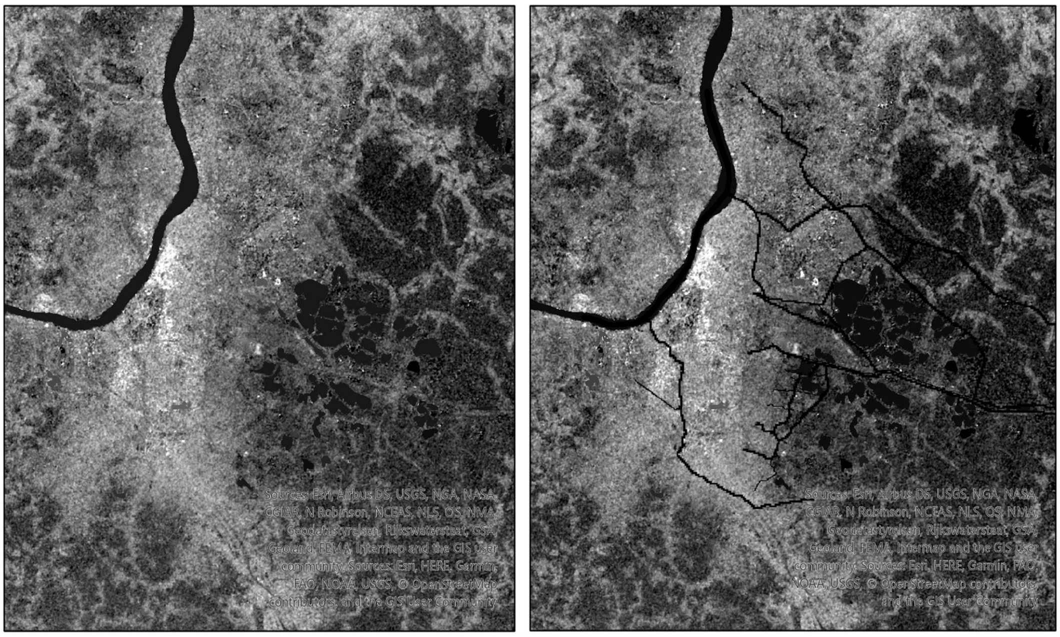

Figure 12. Before DEM Reconditioning tool was applied (left) and after DEM Reconditioning tool was applied. The black lines burned into the DEM in the reconditioned map represent natural and artificial (i.e., man-made) waterways that the DEM resolution quality was too low to capture.

6 Terrain Processing Steps

The following series of steps will create a delineated catchment area grid in which each cell carries a value indicating to which catchment the cell belongs.

6.1 The final reconditioned DEM was input into the “Fill Sinks” tool to massage out the erroneous sinks and depressions.

6.2 The output from the "Fill Sinks" operation was used as the input in the “Flow Direction” tool. This function uses an eight-direction flow model to determine which direction water would flow out of a pixel (i.e., toward the neighboring cell with the lowest elevation). The result was a raster of values that each represent a direction (1=East, 2=Southeast, 4=South, 8=Southwest, 16=West, 32=Northwest, and 64=North).

6.3 The output from the "Flow Direction" function was processed in the “Flow Accumulation” tool to sum the numbers of cells that flow into each pixel. Pixels with relatively high sums are areas where water accumulates to form streams and channels.

6.4 The “Raster Calculator” tool was used to define streams that had flow accumulation > 1,000 cells (Figure 13). This threshold value was selected because the output most closely resembled the waterways map extracted from OSM. The “Stream Definition” tool can also be used for this step. Both tools are

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well documented throughout the literature.

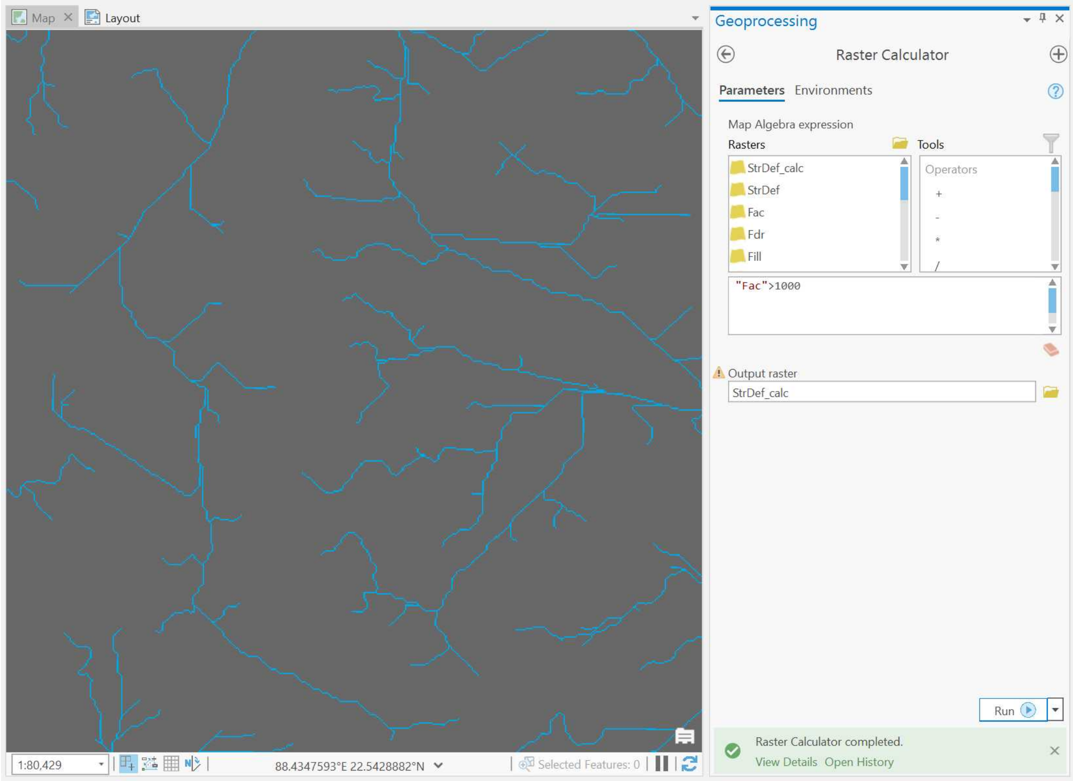

Figure 13. Output from the “Raster Calculator” operation.

6.5 The “Stream Segmentation” tool was then used by inputting the stream raster from the previous step and the flow direction raster to assign a unique ID to each stream segment (Figure 14).

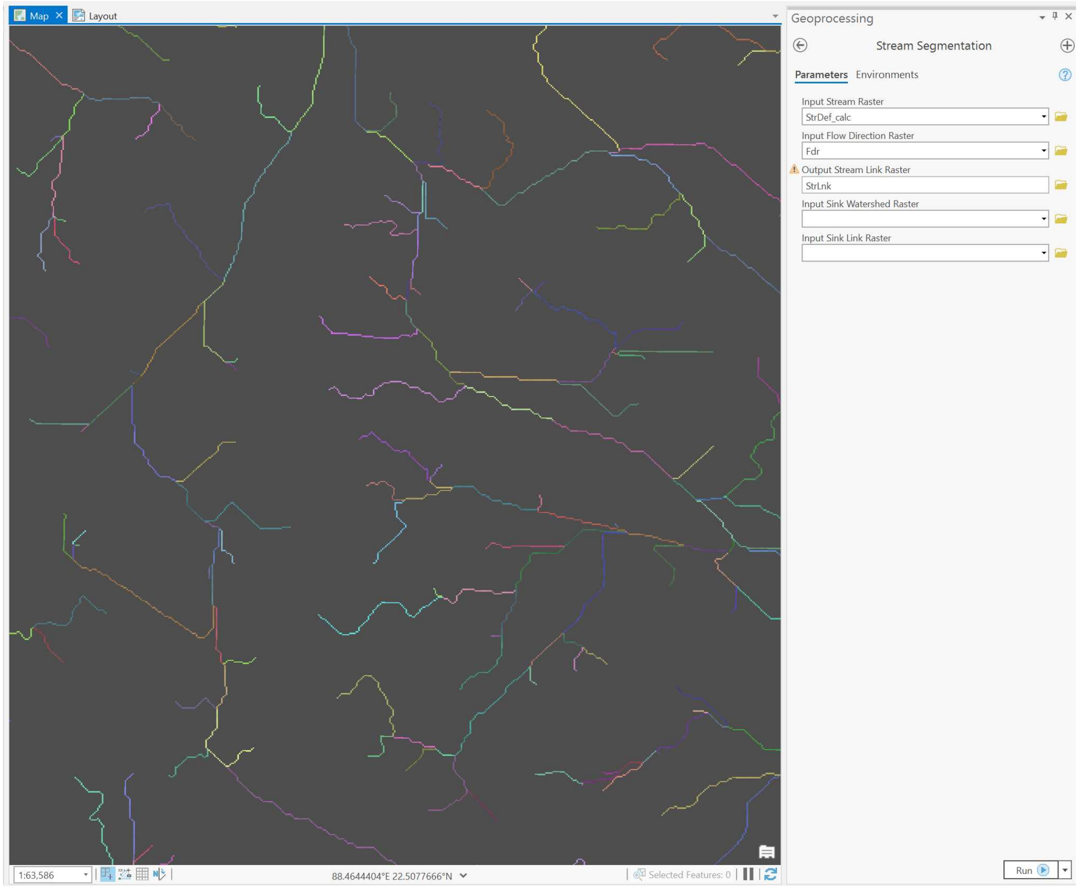

Figure 14. Output from the "Stream Segmentation" operation.

6.6 The "Catchment Grid Delineation" tool was executed to separate the catchment areas and store the information into a grid. The stream segment raster generated in the previous step was input in addition to the flow direction raster to generate the catchment grid. The resulting delineated catchment areas are shown in Figure 15.

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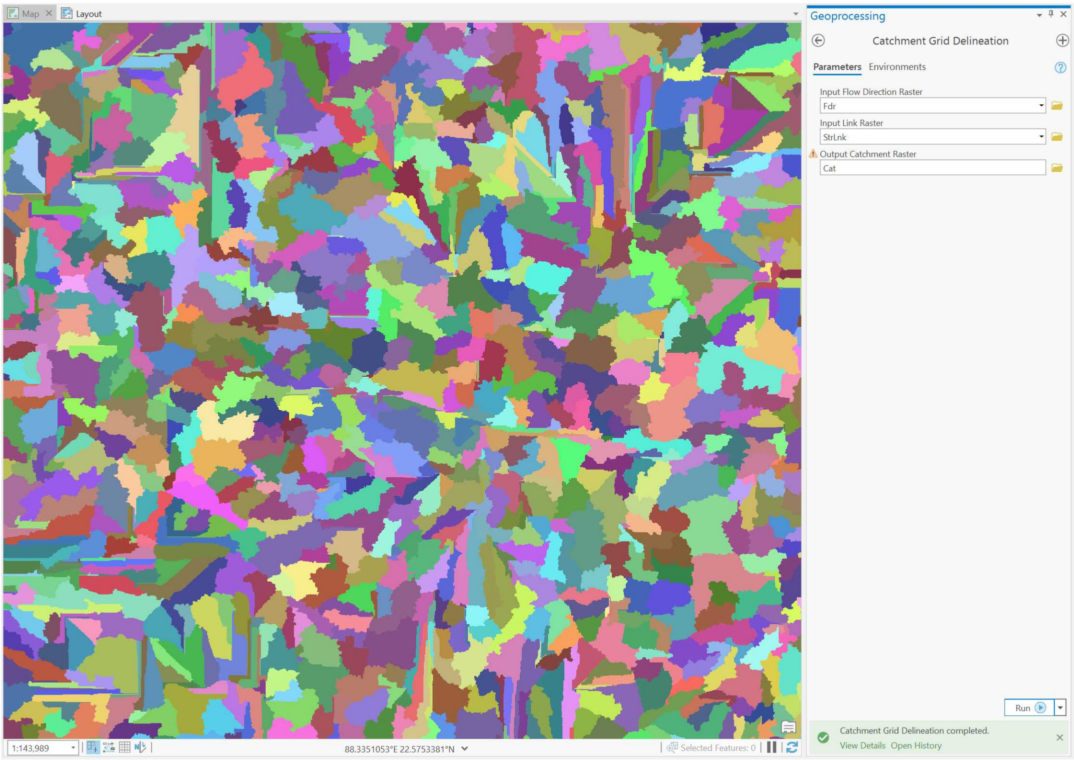

Figure 15. Output from the “Catchment Grid Delineation” operation.

6.7 The “Catchment Polygon Processing” tool was then used to convert the catchment delineation grid into a polygon feature class.

7 Incorporating Sanitation Infrastructure

The sewage drainage system in Kolkata combines wastewater, storm water flow, and dry weather flow into one system through what is called a “water carriage system”. The Hooghly River has tidal gates that allow water from the river to flow into and through the city in a southeasterly direction. Pumping stations installed throughout the city pump wastewater from lower to higher elevation.

7.1 Diagrams that illustrate underground sewer and stormwater conveyance pipes were found online for three drainage systems in Kolkata: Town, Suburban, and Maniktala (Figures 2 - 4). These were manually drawn in ArcGIS Pro using the editing tools.

7.2 Thirteen pumping stations were sampled for this project. Their locations were added to the map. Figure 16 depicts the connections between underground pipes, waterways, and pumping stations.

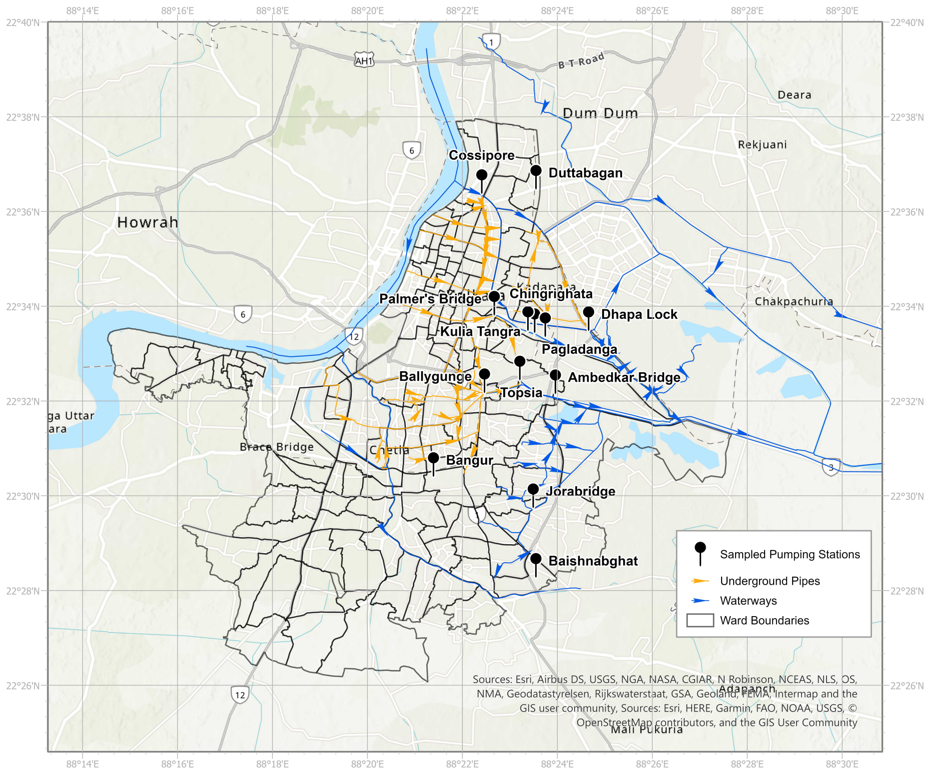

Figure 16. Underground sewer and storm water pipes connect to open canals and waterways in the combined storm and sewer system in Kolkata, India. Pumping stations strategically move wastewater from areas of lower to higher elevation throughout the city.

8 Downloading and Overlaying Population Data

One of the objectives of this research was to improve interpretation of the environmental surveillance results by estimating the population size and geographic area that the pumping station samples represented. Shapefiles of population data were useful for this aspect of the research.

8.1 A shapefile with population data from the India Census of 2011 organized by wards was found within the ArcGIS online gallery. Figure 17 shows population categorization of wards using the Natural Breaks (Jenks) classification.

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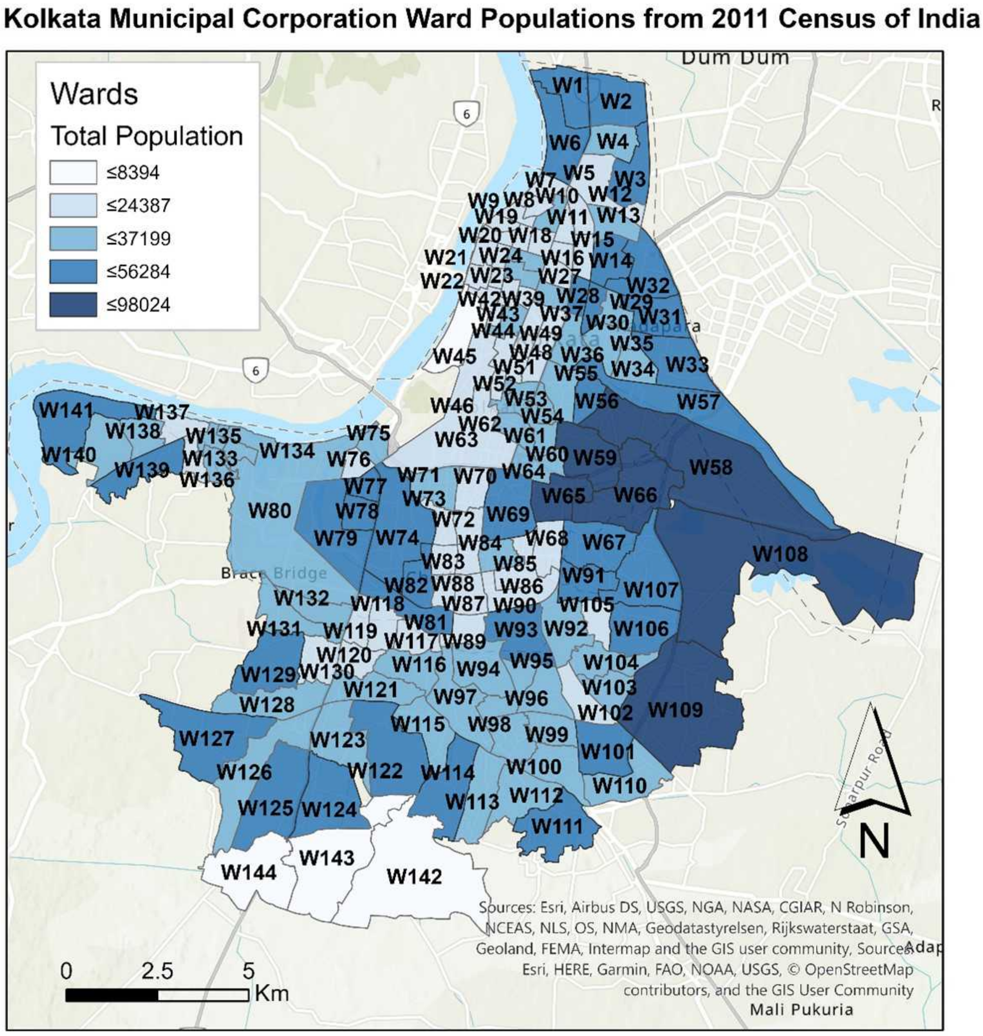

Figure 17. Total population per ward from 2011 Census of India using Natural Breaks (Jenks) classification

9 Estimating Catchment Areas of Sampled Pumping Stations

9.1 A process flow diagram was created to illustrate the decision-making process behind the population estimates for Kolkata and is shown in Figure 18. This diagram is unique to Kolkata because not all urban settings will have a similar knowledge bank to draw from. **A more generalized approach to estimating catchment area population size is presented for the second case study in Accra, Ghana in the next section.**

Citation: Jamie VanTassell, Christine Moe A Mixed-Methods Catchment Area Modelling Approach Using Free DEMs to Inform Environmental Surveillance in Kolkata, India and Accra, Ghana https://dx.doi.org/10.17504/protocols.io.dm6gpwkxdlzp/v1

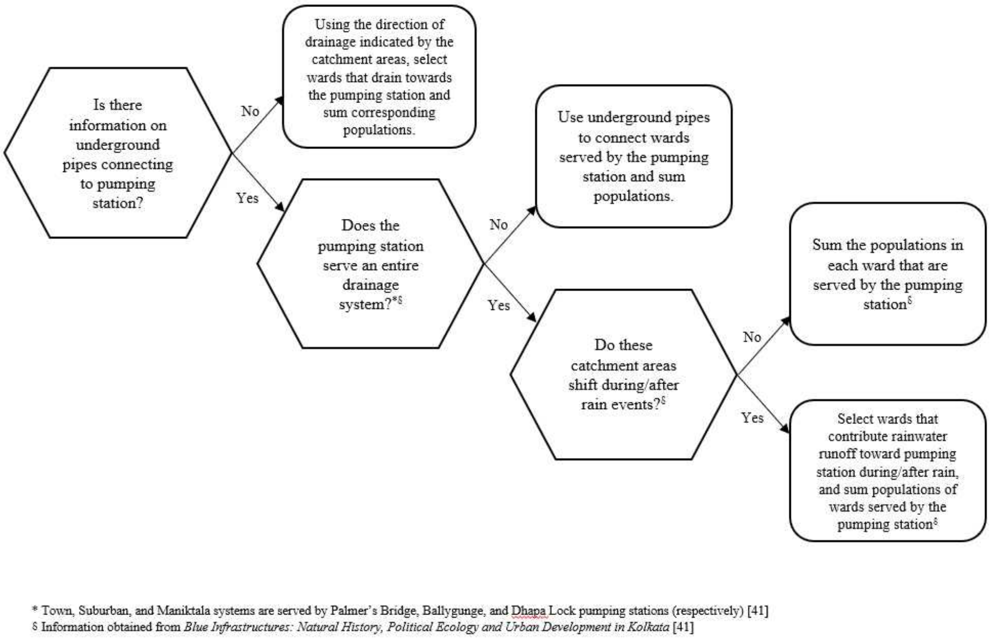

Figure 18. Process flow diagram for selecting method to estimate the population of each sampled pumping station in Kolkata, India

9.2 The population estimate procedure for the Duttabagan pumping station (PS) will be discussed in detail to demonstrate the decision-making process behind the calculations. The Duttabagan PS does not have information regarding the underground pipe network that connects sewer and storm water to it, and it is therefore in the first “No” box in the process flow diagram (Figure 18).

9.3 The delineated catchment grid shown in Figure 19 suggests that the catchment area in which the Duttabagan PS is situated drains southward. A zone above the facility was drawn to capture the upstream catchment area, and it reveals that partial areas of Wards 2, 3, and 4 drain to the Duttabagan PS (Figure 20).

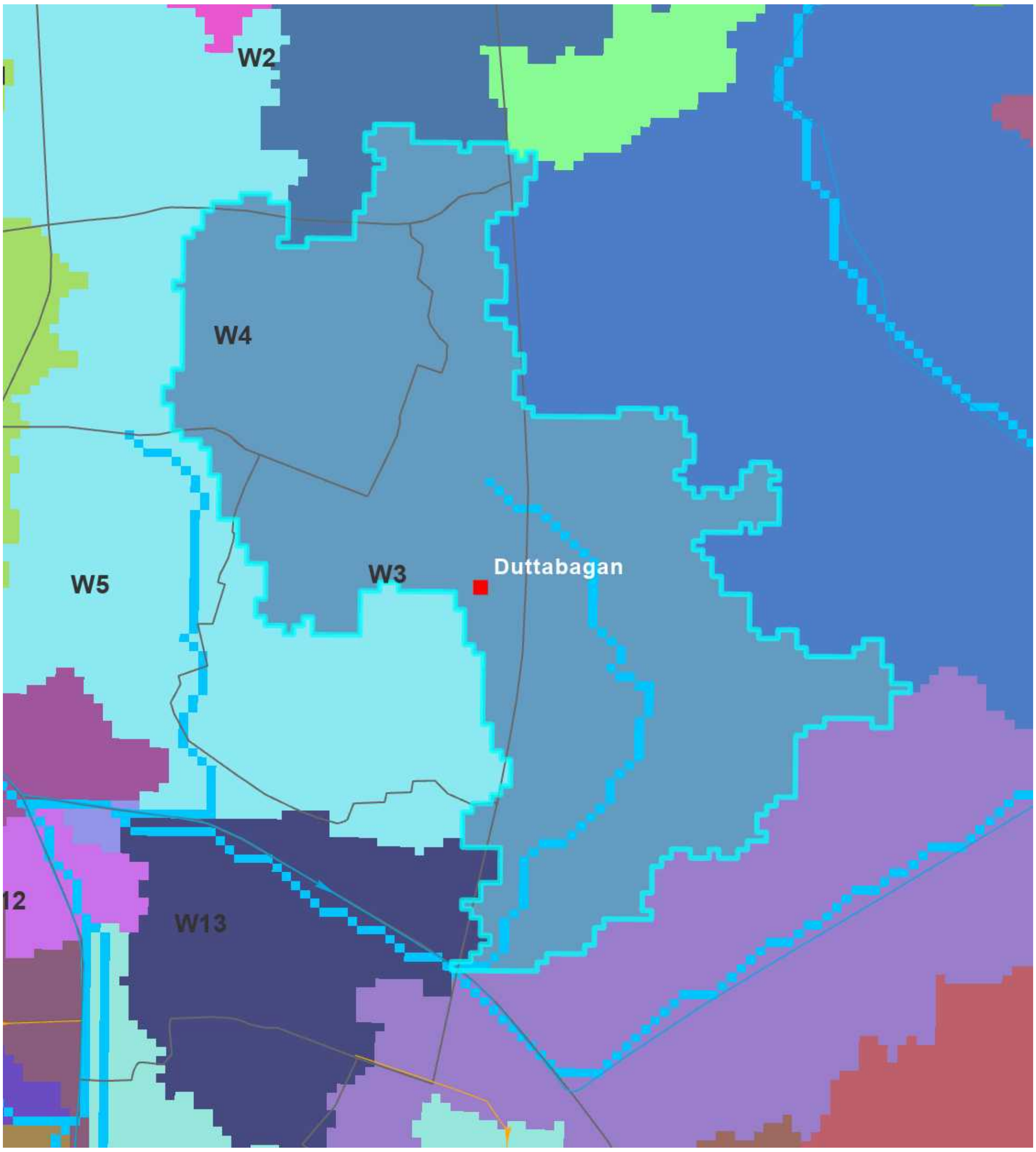

Figure 19. Primary catchment area in which Duttabagan PS is situated within.

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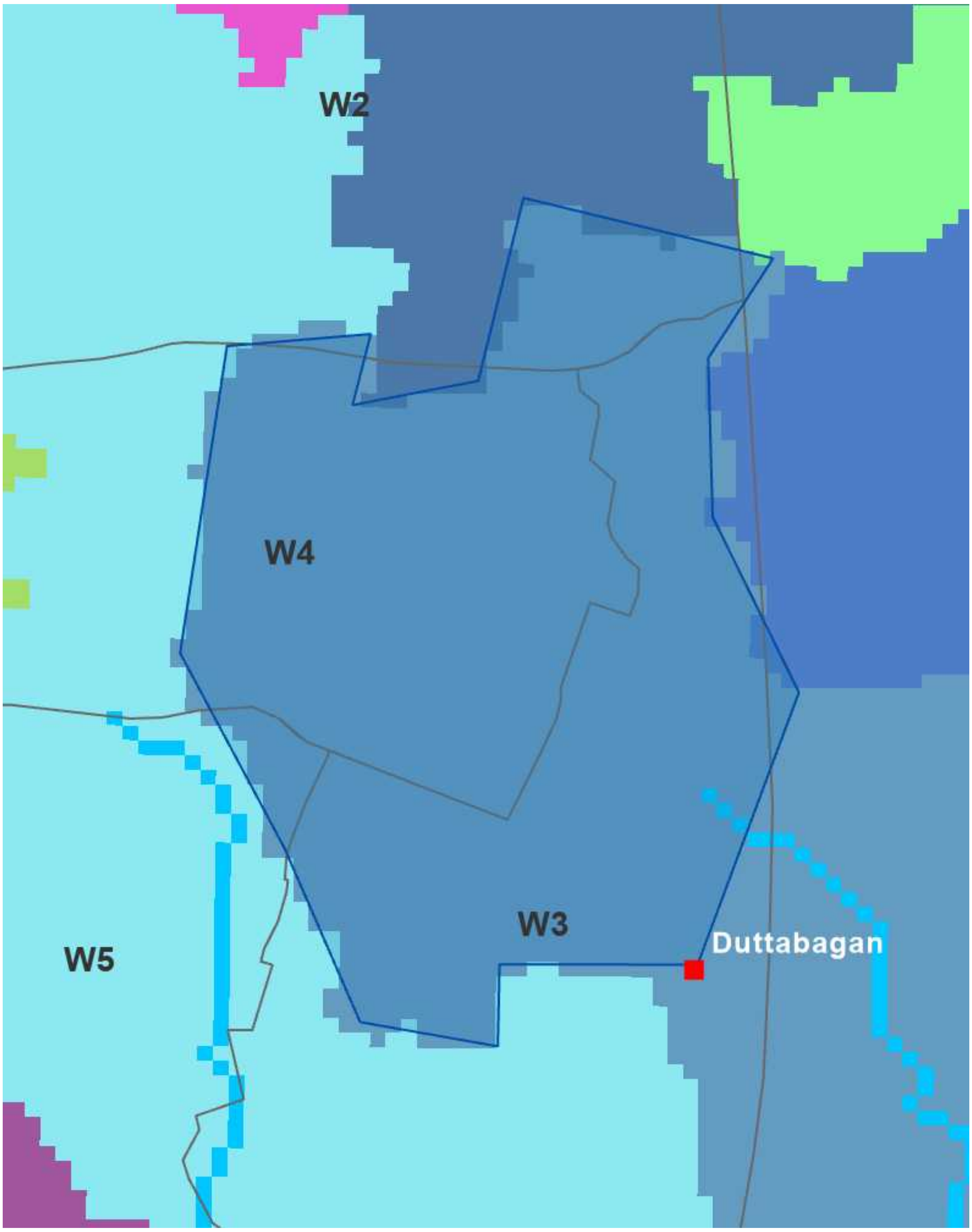


Figure 20. Polygon drawn to estimate the upstream catchment area of the Duttabagan PS.

9.4 The “Tabulate Intersection” tool was then applied to determine the percentage of area that each ward shares with the upstream catchment area (i.e., the drawn polygon in Figure 20). The inputs into this tool are shown in Figure 21, and the output table results are shown in Figure 22.

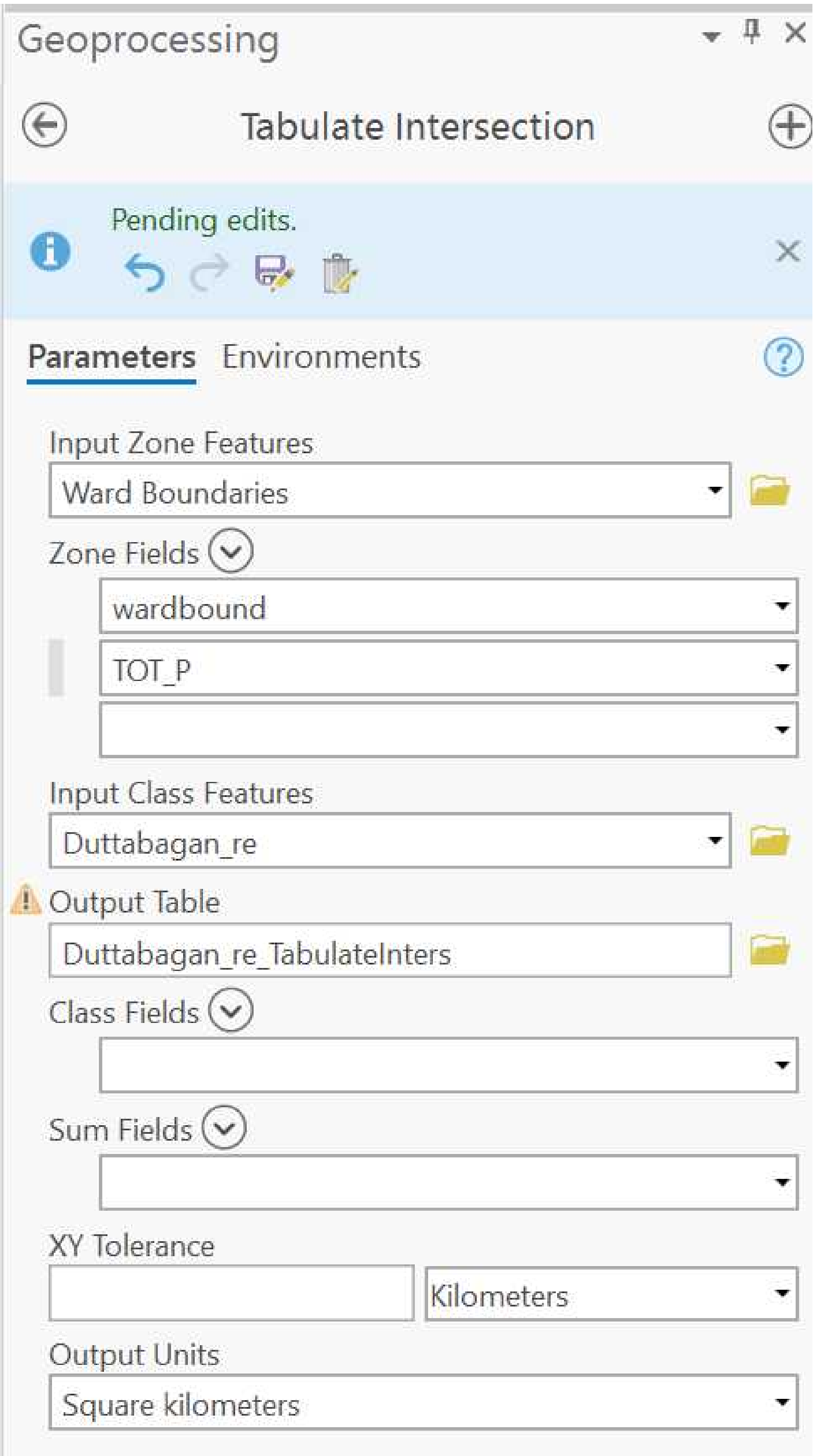
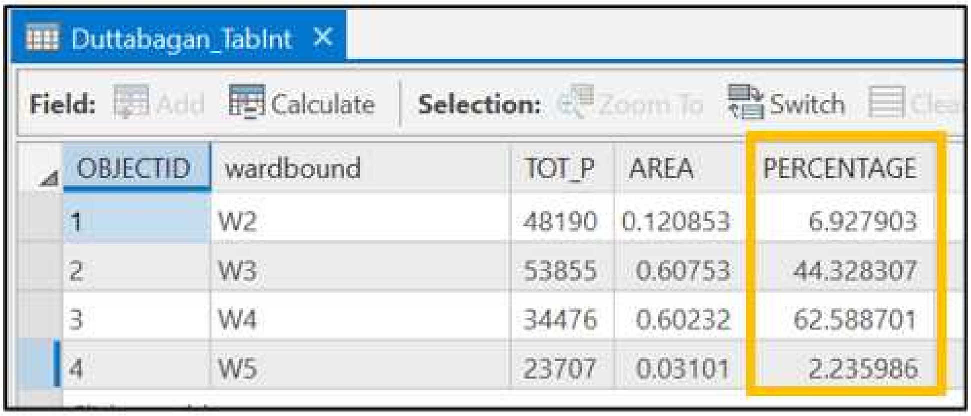


Figure 21. Inputs into "Tabulate Intersection" tool.



Duttabagan_TabInt

Field: Add Calculate Selection: Zoom To Switch Clear

OBJECTID	wardbound	TOT_P	AREA	PERCENTAGE
1	W2	48190	0.120853	6.927903
2	W3	53855	0.60753	44.328307
3	W4	34476	0.60232	62.588701
4	W5	23707	0.03101	2.235986

Figure 22. Screenshot of outputs from the “Tabulate Intersection” operation. The percentage column, outlined in orange, is used to calculate how much of the total population in each ward is served by the pumping station.

9.5 The percentages from the orange "PERCENTAGE" column in Figure 22 were multiplied by the total population (column "TOT_P") in each corresponding ward and summed to calculate the total population of the catchment area. Therefore, the population size contributing to the Duttabagan PS is estimated to be 49,788 people.

9.6 Steps 9.4 - 9.5 were repeated for all of the sampled pumping stations to calculate the population size of each catchment area. The process and rationale for estimates for each pumping station is provided in the PDF attachment.

Population Estimates of Sampled Pumping Stations in Kolkata.pdf

Case Study #2: Accra, Ghana

10 Investigative Research

The sewer system and terrain of Accra is very different from Kolkata, and this affected how the Accra model was built.

10.1 Research was first performed to gain an understanding of the sanitation infrastructure in Accra Metropolitan Area (AMA), but it was a less robust process compared to the research performed for Kolkata because the sewer system in Accra has less hydraulic structures that disrupt the natural flow of wastewater. After conversations with local partners in the TREND Group (a local environmental consulting group that specializes in sanitation), no pumping stations were added to the model because the few existing facilities were nonfunctional. In addition, underground sewer and storm water lines were not incorporated because these structures are not common in the AMA. Owing to the city’s primary reliance on vehicle transport of excreta for treatment/disposal and the common practice of discharging excreta into open drains, it was assumed that these structures would have a negligible impact in the model.

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There is a vast network of open drains throughout Accra that are intended to collect and drain storm water, although wastewater and solid waste are often deposited into these drains. Accra is a hilly, coastal city, and open drains connect to larger waterways which drain by gravity to the ocean. Although maps of open drains were not available for all of the neighborhoods in Accra, a hydrologic model is able to capture these complex networks because open drains flow by gravity into larger waterways. Therefore, strategic sampling points along the larger waterways capture areas from which excreta is discharged into open drains.

Open defecation has been declining in recent years, but it has not been completely eliminated. This is relevant to the Accra model because feces in the environment may follow DEM-derived drainage routes after heavy rain events (assuming there are limited barriers). Once excreta are washed into waterways, it can be captured in environmental samples. Pit latrines and septic tanks are commonly used to hold sewage in Accra, and the contents are emptied and trucked offsite to facilities for disposal and/or treatment. It is important to note that the catchment area model developed for Accra was not able to capture the movement of sewage that was transported from holding reservoirs to offsite facilities.

11 **Building the Model**

For Kolkata, upstream catchment areas of previously sampled pumping stations were approximated using a hybrid hydraulic - hydrologic model to improve interpretation of the results from an environmental surveillance study. In contrast, the hydrologic model built for Accra shows how GIS can be used to pro-actively identify strategic sampling points for environmental surveillance.

11.1 Similar to Kolkata, the DEM for Accra was downloaded from USGS EarthExplorer (see Step 2 for instructions).

11.2 Waterways shapefiles were extracted in QGIS using the QuickOSM plugin and edited to match waterways observed in the Google Terrain basemap (see Step 3 for instructions). Only one waterway feature was created for Accra due to their being less variation in stream widths.

11.3 The DEM for Accra was imported into ArcGIS Pro and re-projected to “WGS 1984 / UTM Zone 30N” using the "Project Raster" tool.

11.4 The waterways shapefile from QuickOSM was converted to a raster using the "Feature to Raster" tool and re-projected to “WGS 1984 / UTM Zone 30N”.

11.5 The waterways raster was input into the "DEM Reconditioning" tool within the Arc

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Hydro toolkit and executed using the default settings for number of cells for stream buffer and the smooth/sharp drop in Z units. These settings were considered appropriate for Accra's hilly terrain.

11.6 The reconditioned DEM was input into the “Fill Sinks” tool to massage out the erroneous sinks and depressions.

11.7 The output from the "Fill Sinks" operation was used as the input in the “Flow Direction” tool. This function uses an eight-direction flow model to determine which direction water would flow out of a pixel (i.e., toward the neighboring cell with the lowest elevation). The result was a raster of values that each represent a direction (1=East, 2=Southeast, 4=South, 8=Southwest, 16=West, 32=Northwest, and 64=North).

11.8 The output from the "Flow Direction" function was processed in the “Flow Accumulation” tool to sum the numbers of cells that flow into each pixel. Pixels with relatively high sums are areas where water accumulates to form streams and channels.

12 Evaluating Population and Demographic Data

Depending on the goals of the environmental surveillance system, population and demographic spatial data can be used to steer the site identification process. For example, if the primary focus is to monitor low-income neighborhoods, points can be selected that are downstream of these areas. Figures 23 and 24 below show examples of other spatial data that can influence the sampling site selection process.

12.1 A shapefile of 2010 census data for neighborhoods in Accra was utilized to visualize key characteristics of the Accra Metropolitan Area, such as population size, SES, open defecation, WASH infrastructure, and history of cholera outbreaks. Figures 23 and 24 show population counts and open defecation rates by neighborhoods in the AMA.

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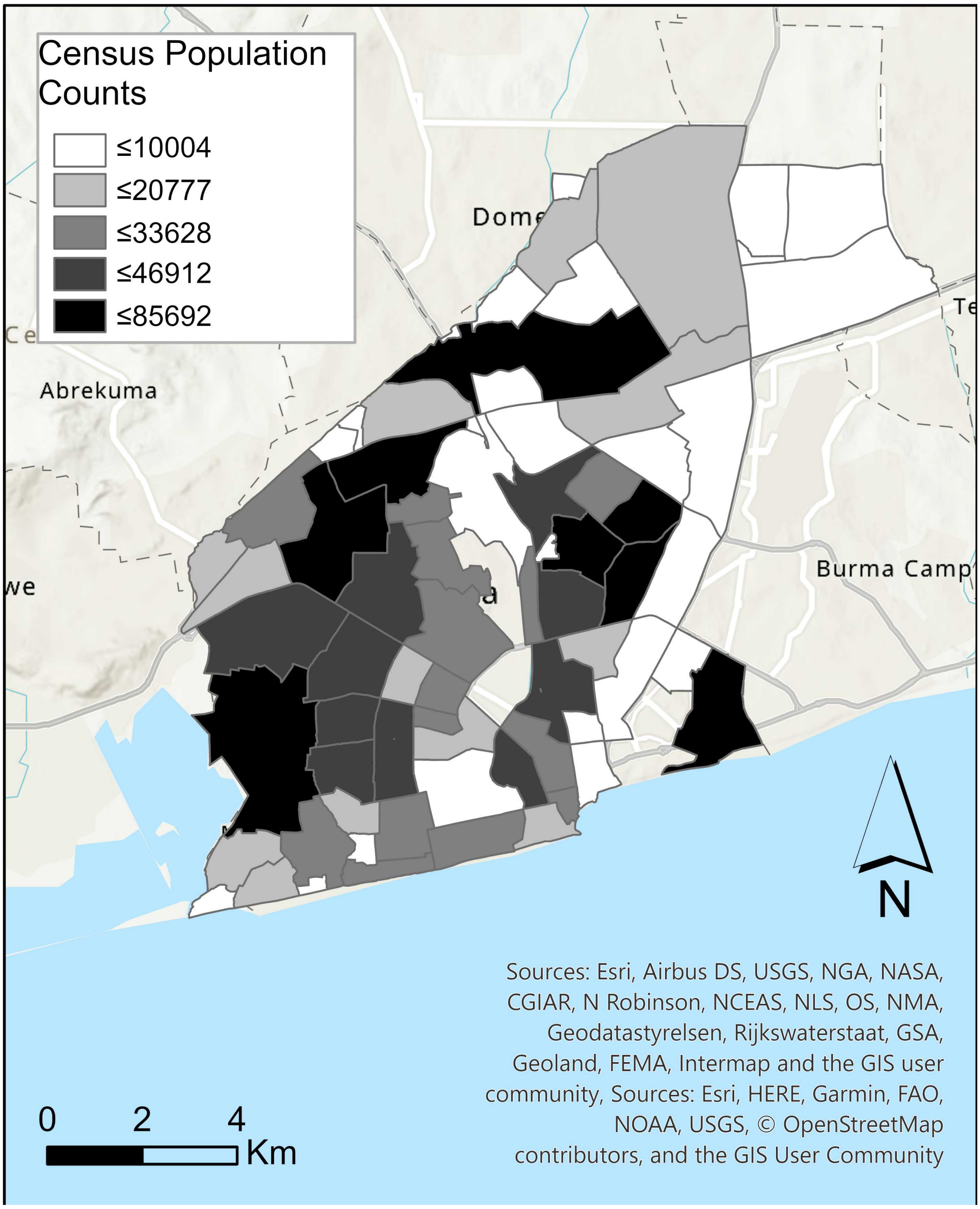

Figure 23. Population counts by neighborhood in the Accra Metropolitan Area.

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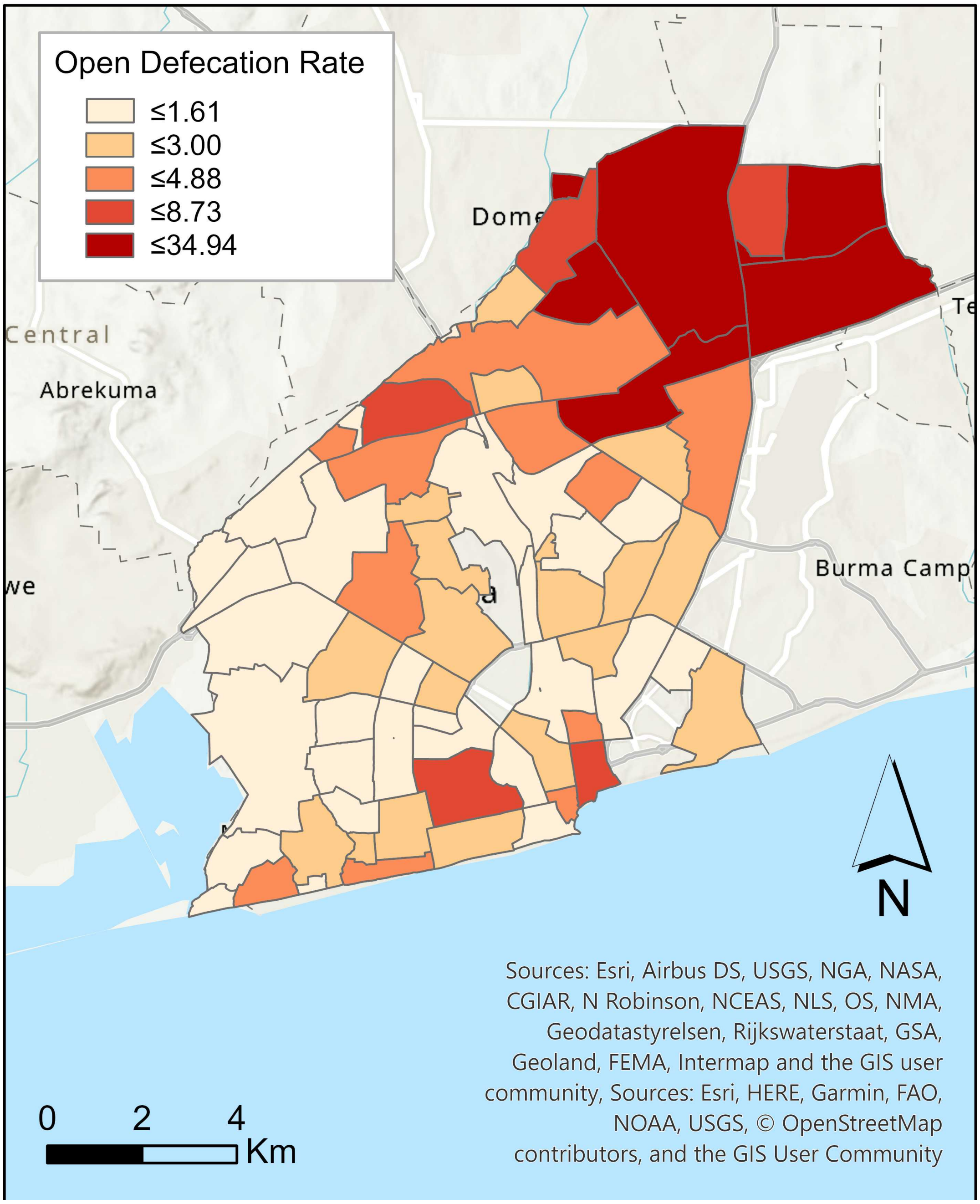

Figure 24. Open Defecation Rate by neighborhood in the Accra Metropolitan Area.

13 Creating Pour Points

A pour point is the point on a map at which water from a specified watershed flows out of an area. It is the lowest point of the watershed. Pour points will be added to the map with their corresponding watersheds to illustrate examples of strategic sampling points that could be used for environmental surveillance.

13.1 Within the Catalog pane, a new shapefile was created in the project workspace by right-clicking the destination folder and selecting "New" and then "Shapefile".

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13.2 In the Geoprocessing pane, the Feature Class Name was titled "PourPoints", and the Geometry Type selected from the drop-down list was "Point". The Coordinate System was set to “WGS 1984 / UTM Zone 30N”, and the operation was run.

> If the new shapefile was not added to the map (i.e., it is not showing in the Contents pane), right-click the shapefile in the Catalog pane and select "Add to Current Map".

13.3 In the "Edit" tab at the top of the screen, "Create" was selected. In the Create Feature pane, "PourPoints" was clicked and the icon to create a new point was selected.

13.4 Ensure that the Flow Accumulation layer is turned on so that it appears on the map. Zoom in to add points to nodes on these stream lines. If smaller catchment areas are desired, points should be placed along nodes further away from high flow accumulation streams. Conversely, to create large catchment areas, points should be added to nodes closer to high flow accumulation streams (see Figure 25 for examples).

> - The point must be placed *within* the flow accumulation line (zoom in very close to ensure this happens).
> - Watching a YouTube video of this process can be very helpful. Here is a link to one tutorial: https://www.youtube.com/watch?v=jblvDgfK7Lc
> - Recall from Step 12 that population and demographic data can be used to identify strategic sampling sites that capture areas of interest (e.g., areas with high population, lower SES, higher rates of open defecation, etc.). If specific areas are desired for surveillance, search for sites that are downstream of those areas.

Citation: Jamie VanTassell, Christine Moe A Mixed-Methods Catchment Area Modelling Approach Using Free DEMs to Inform Environmental Surveillance in Kolkata, India and Accra, Ghana https://dx.doi.org/10.17504/protocols.io.dm6gpwkxdlzp/v1

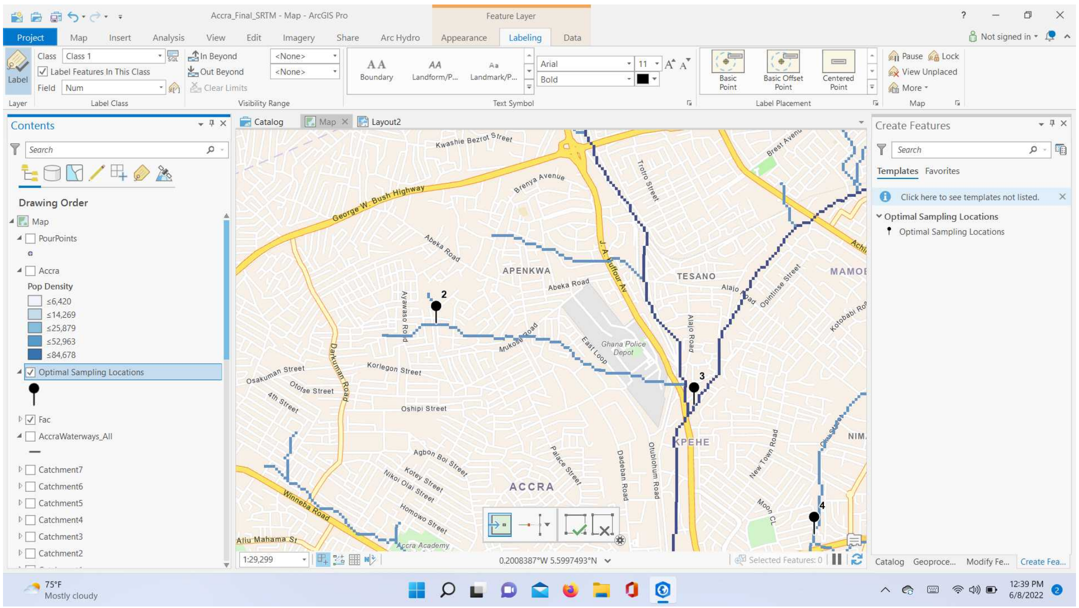

Figure 25. Point 2 is an example of a point that will result in a smaller upstream catchment area because it is further away from the high flow accumulation streams. Point 3 is an example of a point that will create a larger catchment area because it is close to the high flow accumulation stream.

13.5 Add points to the PourPoints shapefile until a satisfactory number of sites is reached. The total number of sites and size of the catchment areas will depend on the objectives of the surveillance system. For this model, seven sites were identified to showcase varying sizes of catchments areas upstream of sampling sites (Figure 26).

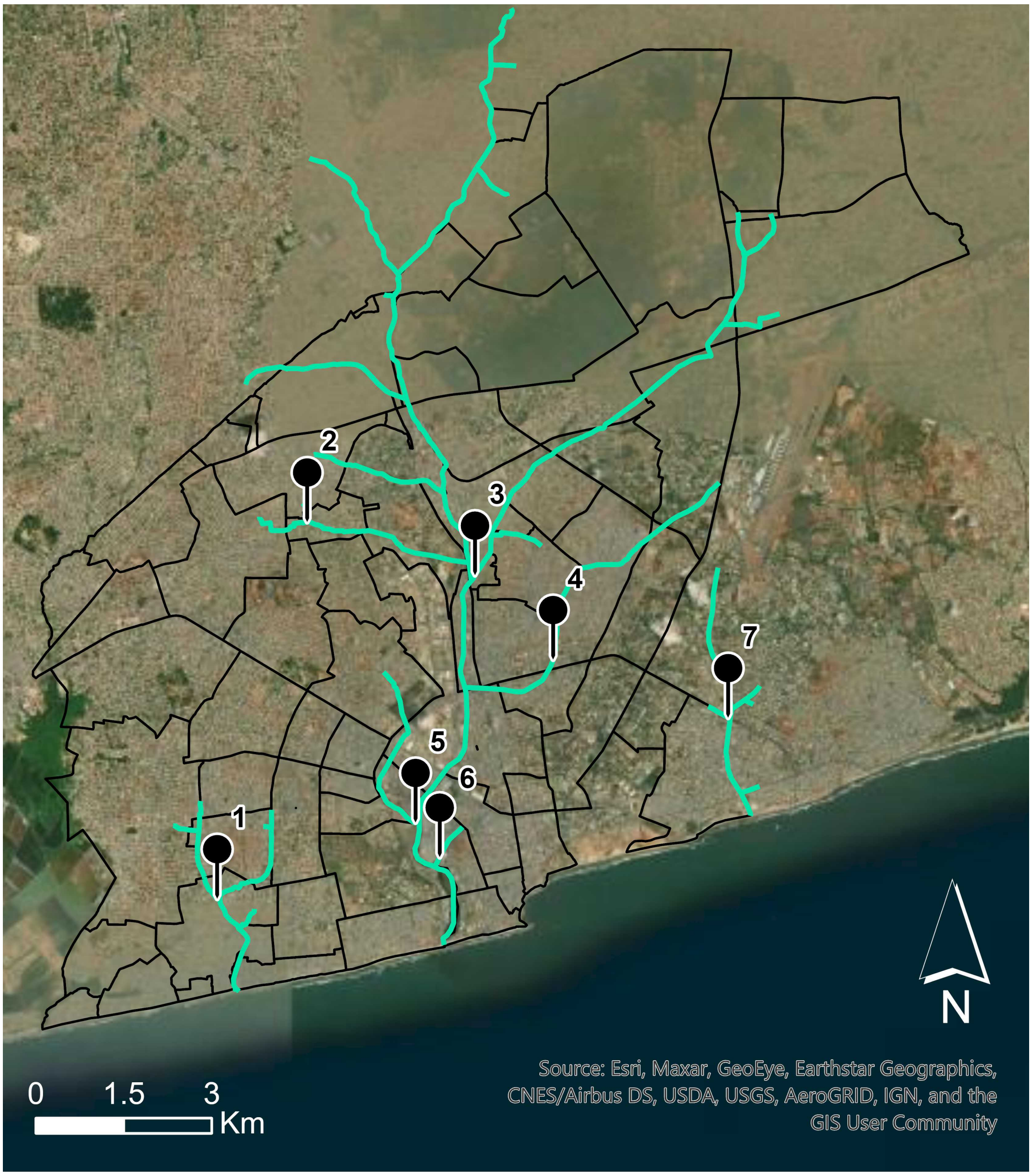

Figure 26. Seven strategic sample collection sites were identified. Preference was given to pour points downstream of areas that had a relatively higher population count, lower SES status, higher rates of open defecation, and/or history of cholera outbreaks because these factors were assumed to potentially have a positive association with infectious disease transmission.

14 Creating Watersheds/Catchment Areas

14.1 In the Analysis tab, select the "Watershed" tool within the Spatial Analyst toolkit. Input the flow direction raster and PourPoint shapefile. In the "Pour point field", select a field that has a unique identifier for each points (e.g., FID, OBJECTID).

The upstream catchment areas captured by the seven sampling points are

14.2 shown in Figure 27. These seven locations were selected to illustrate how this method can be used to identify sampling locations with optimal population coverage without overlapping catchment populations. More locations could be added to achieve higher population coverage in the model. The locations of the sampling points can be moved upstream or downstream to decrease or increase the size of the upstream catchment area.

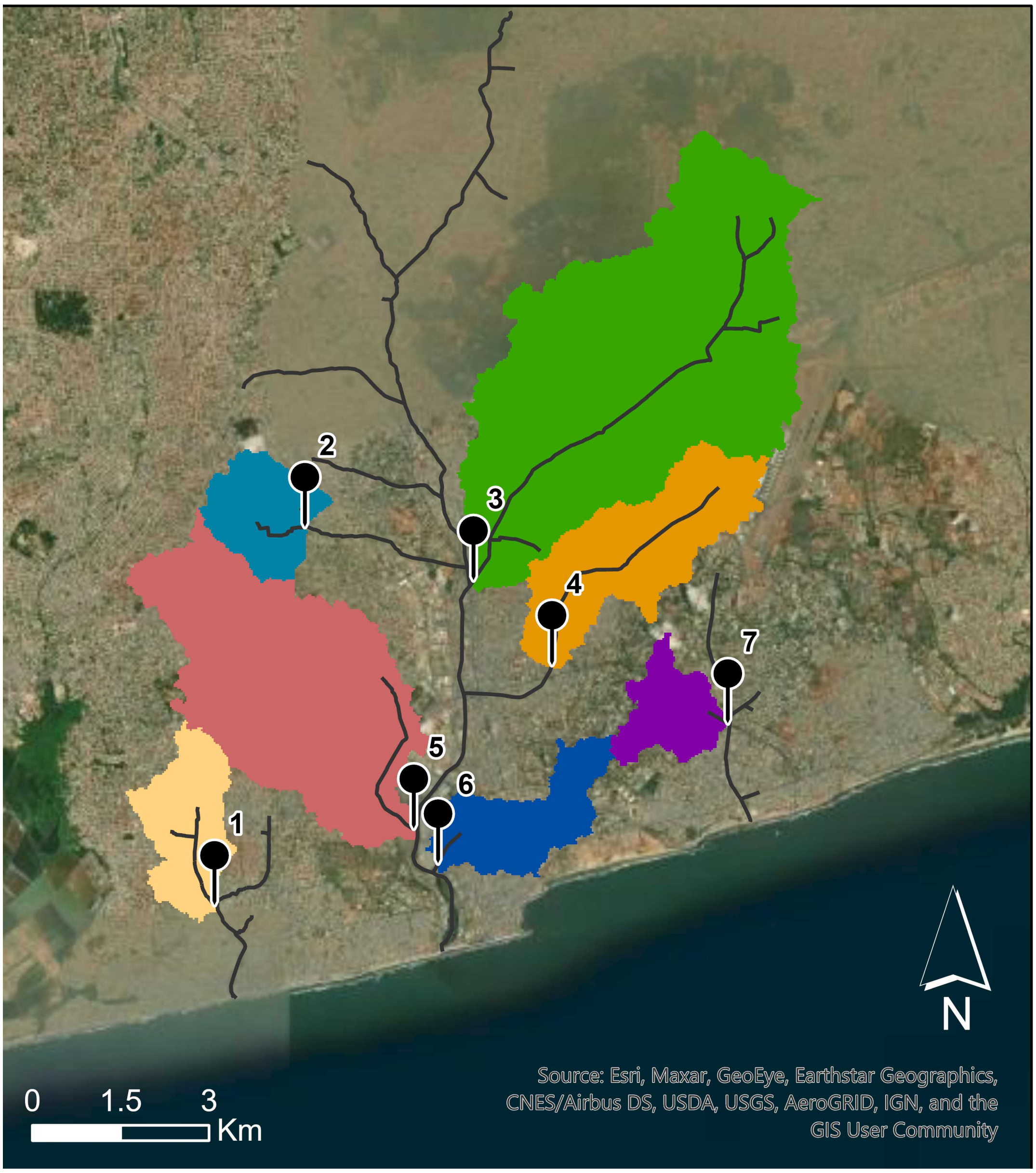

Figure 27. Upstream catchment areas of seven examples of strategic sampling points that could be used for environmental surveillance.

14.3 The "Catchment Polygon Processing" tool was then used to convert the catchment areas from the last step into a polygon feature class.

15 **Estimating Population Size**

This procedure mimics the methods used for Kolkata in which the intersection between catchment areas and wards was calculated to estimate the catchment population size.

15.1 The “Tabulate Intersection” tool was used to determine the percentage of area that each neighborhood shares with the upstream catchment area of the pour point. The inputs into this tool are shown in Figure 28 for Sampling Site 2 and its upstream catchment area, and the results are shown in Figure 29.

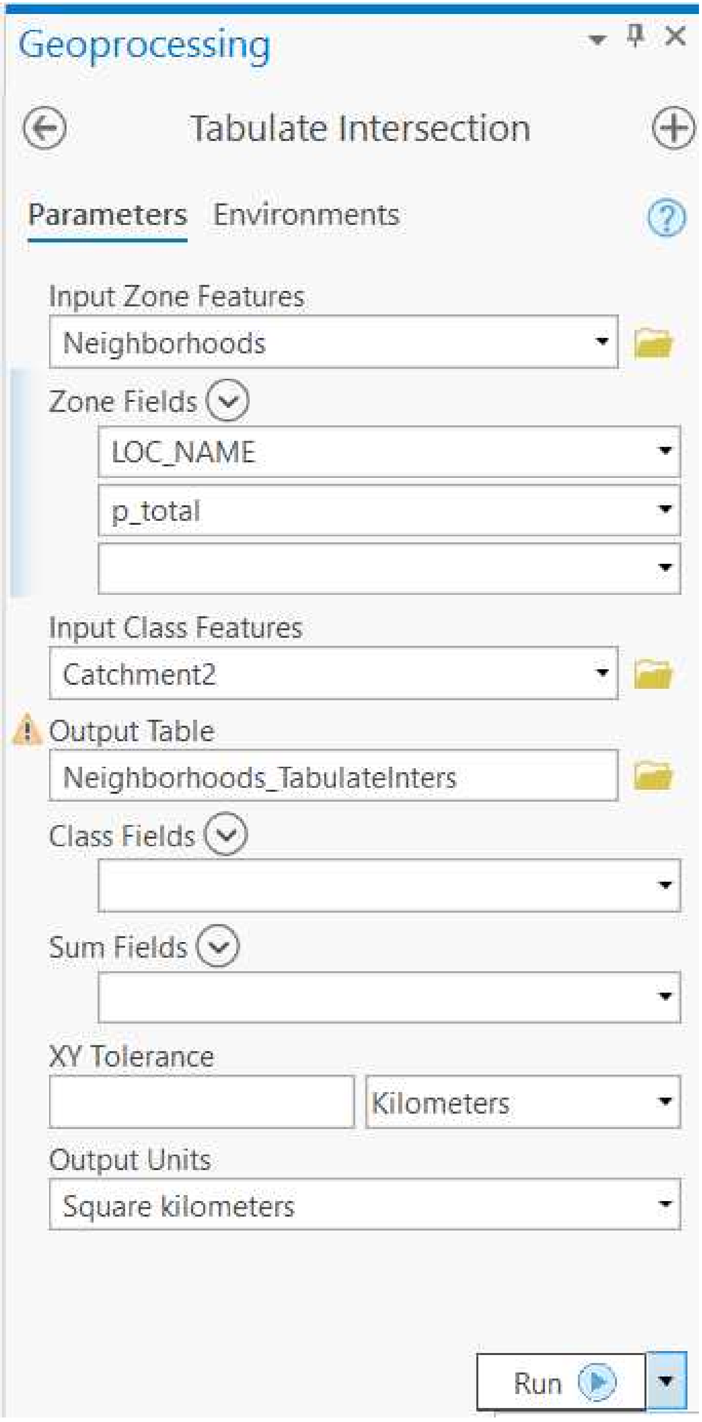

Figure 28. Inputs into the "Tabulate Intersection" tool for Catchment Area 2 for the Accra model.

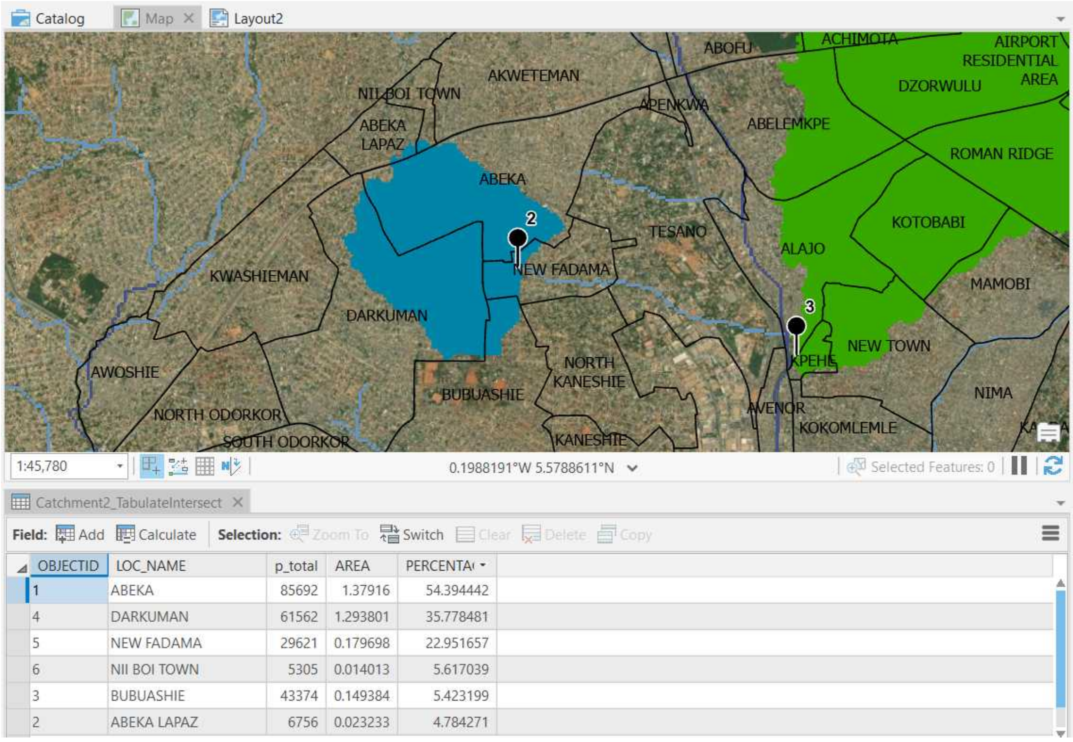

Figure 29. Screenshot of outputs from the "Tabulate Intersection" operation.

15.2 The percentages column was multiplied by the total population ("p_total") column and summed to calculate the total population of the catchment area. Therefore, the population size estimate for Sampling Site 2 is 78,410 people.

15.3 Steps 15.1 - 15.2 were repeated for all of the sampling sites. Population estimates for each of the seven sites can be found in the attached spreadsheet.

AccraPopEstimates.xlsx